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ENVIRONMENTAL STATUS OF THE LAKE MICHIGAN REGION

VOLUME 8. ATMOSPHERIC ENVIRONMENT OF THE LAKE MICHIGAN DRAINAGE BASIN

DONALD F. GATZ AND STANLEY A. CHANGNON, JR.

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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ENVIRONMENTAL STATUS OF THE LAKE MICHIGAN REGION

Volume 8. Atmospheric Environment of the Lake Michigan Region

by

Donald F. Gatz* and Stanley A. Changnon, Jr.*

Consultants to
Division of Environmental Impact Studies

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*Illinois State Water Survey, Urbana

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PREFACE

Assessments of the environmental impacts of individual nuclear power plants sited on the shores of Lake Michigan have led to increased recognition of the need for regional considerations of the environmental impacts of various human activities, and a compendium of information on the environmental status of the region for use in assessing such impacts. In response to these needs, a report series describing the status of Lake Michigan and its watershed is in preparation. This series is entitled "Environmental Status of the Lake Michigan Region"; this report is part of that series.

The report series provides a reasonably comprehensive descriptive review and analysis of natural features and characteristics, as well as past, present, and proposed natural processes and human activities that influence the environmental conditions of Lake Michigan, its watershed, and certain adjacent metropolitan areas. This series will constitute a regional reference document useful both to scientific investigators and to other persons involved in environmental protection, resource planning, and management. In these regards, the "Environmental Status of the Lake Michigan Region" will serve in part as an adjunct to reports of broader scope, such as the Great Lakes Basin Commission's Framework Study.

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VOL. 8. ATMOSPHERIC ENVIRONMENT OF THE LAKE MICHIGAN REGION

by

Donald F. Gatz and Stanley A. Changnon, Jr.

Abstract

Climate was the most important factor in producing the Great Lakes we have today. Through glacial action during the Pleistocene Epoch, the surface topography, shape, and depth of Lake Michigan were determined. Today the Lake Michigan region has a humid, continental climate. Summers are hot and humid, and winters are cold and stormy. Lake Michigan, as a reservoir for storing and exchanging heat is a moderating influence on extreme temperatures. The Lake is also a moisture source, especially during late fall and early winter when Arctic air flows over the still-warm lake. Heavy snows in the lee of the Lake can result.

Regional atmospheric dispersion conditions are generally good in locations away from the Lake. Air mass stagnation conditions are expected only four times a year, and three of these should last no longer than two days each. However, over and near the Lake, conditions can be extremely different. During the warm season, when the air over the Lake is relatively cold and stable, onshore airflow can produce a number of conditions leading to high pollutant concentrations within 10 km of the Lake shore. The pollutants also have effects on the weather, including reduced visibility and solar radiation, and increased cloudiness. They may also play a role in producing excess precipitation downwind of large industrial and population centers. Atmospheric pollution also provides an important pathway for the transfer of pollutants deposited on the Lake surface both by dry fallout and in precipitation.

INTRODUCTION

The atmosphere is an essential component in any discussion of environmental aspects of the Lake Michigan region. Historical climatic variations produced the glaciers that determined the basic physical characteristics of the Lake and its surroundings as we know them today. Climate, and temperature in particular, has been a primary control on the kinds of plants and animals that live in the region, from historical times up to the present.

There are two main goals for this report: (*i*) to describe current climatic conditions and trends, and (*ii*) to describe the atmospheric processes that must be considered in regional environmental impact assessments of additional pollutant sources. This report is for a broad spectrum of persons concerned with the present and future status of the Lake Michigan region (a map of Lake Michigan and the surrounding states is shown in Fig. 1). Individual subjects are treated to the depth necessary to emphasize their importance and to describe their basic physical nature. Literature references are provided for those who need more information.

The report is divided into two parts. Part 1 is devoted to traditional aspects of climatology. It begins with a summary of the general climate of the region and Lake Michigan's influence on it. This is followed by a description of historical climatic fluctuations and their influence on the region's landforms and biota. A detailed current climatology of the region follows. Here we emphasize the time and space variability of such weather variables as temperature, moisture, wind, clouds, sunshine, and special weather phenomena, and the Lake's influence on them. Part 2 is devoted to air pollution climatology. Atmospheric influences on pollutant concentrations are discussed, from emission, through transport and transformation, to deposition. The Lake's effects on shoreline meteorology are complex and important to pollutant concentrations. Part 2 concludes with a discussion of the role of the atmosphere as a source of pollutants to Lake Michigan.

PART 1. CLIMATOLOGY

SUMMARY DESCRIPTION OF GENERAL CLIMATE

The Lake Michigan region has a climate described as humid continental. It features hot and humid summers, extremely cold and stormy winters, and extremes of temperature. The humid continental climate of the region is a reflection of the continental and hemispheric conditions that control the climatic types of the Midwestern United States.

Various measures of climatic conditions reflect the variability from day to day, season to season, and year to year which typifies the climate of the Lake Michigan region. Meigs and DePercin (1957) developed a measure of combined cold and wet conditions for North America; their results indicate 35-40 hr/yr in the Lake Michigan region, the highest figure in the United States. Conrad and Pollak (1950) developed a measure of continentality which is a latitude adjusted measure of the annual range of temperatures. The range in the Lake Michigan region is typically 13°C (23°F),* ranking the area second only to the 17°C (31°F) values in extreme northern Minnesota and North Dakota. The degree of continentality and variability of the climate is further reflected by the temperature-humidity index (Thom, 1956) which has values of 24°C (75°F) in the Lake Michigan region, second only to the nation's highest values along the Gulf Coast.

This section of the report presents a summary description of the factors that control the climate of the Lake Michigan region and briefly describes that

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**Throughout this report, measured values are metric units, followed by English units in parentheses. Usually, the original measurements were English units. In converting, the metric value is generally given to the same number of significant figures as the original English value. Thus, conversions are frequently approximate.*

Fig. 1. Lake Michigan and Surrounding States.

climate. However, an adequate understanding of the climate of the Lake Michigan region first requires a brief examination of the climatic controls of North America.

CLIMATIC CONTROLS OF NORTH AMERICA

All five major climates of the world are found in North America. North America is the third largest land mass of the earth and it is compact in its form. The only inland sea is Hudson Bay which, because it is largely ice covered, has little impact on the climate, whereas the Great Lakes, though much smaller, have a greater influence on the climate. The west coast of the continent lacks large indentations which, if they existed, would allow greater moderation of the air masses over the central United States. Another important physiographic factor is the western mountain system. It runs north to south and rises steeply from the Pacific Ocean forming several parallel ranges and basins that are from 800 to 1600 km (∿500 to 1000 mi) wide, all of which makes it a formidable barrier to the prevailing westerly winds. East of the mountains are generally flat lands including the vast lowland in the middle of the continent which extends from Hudson Bay to the Gulf of Mexico and includes the Great Lakes area. Since there is no east-to-west ridge of mountains in the eastern half of the continent (such as found in Europe and Asia), there is a wide open passage for air movement, either from the frozen wastes of northern Canada or from the subtropical Gulf of Mexico. Thus, the shape, size, and surface topography of North America set the stage for the climate of the continent.

What controls the climate? Over any continent six factors interact to produce the various climates found, and the climate in any given area is a result of at least two of these six factors (Kendrew, 1953).

The most significant worldwide climatic control is solar energy at a given latitude. The compactness and considerable north-south extent of North America (10° N to 80° N latitude) bring about a great degree of differential heating which in turn creates great air mass differences. The latitudinal extremes thus result in great temperature extremes that have a direct effect in the development of the major winter cyclonic storms of North America.

A second climatic control is a mountain barrier, and that of the western third of the continent serves as an effective barrier and moderator of the westerly flow from the Pacific Ocean. The Appalachians have some minor effect on the movement of storms and their local climate.

A third climatic control is the land-water indentations. Of particular impact in the climate of North America is the Gulf of Mexico indentation. This warm moist body greatly affects air masses over the eastern half of the United States, and the land-water distribution greatly affects the placement of pressure centers within the continent which in turn affects the air motions.

A fourth climatic control of North America is the oceans and their cold and warm currents. The three major bodies which have a great climatic effect are the North Pacific Drift which affects the West Coast, the Gulf Stream which affects the East Coast, and the Gulf of Mexico which affects the central and eastern United States. Within this area of marine climatic control we include the Great Lakes which have effects primarily on the climate of the Great Lakes region.

A fifth climatic control active in North America is storms. This includes hurricanes, major winter cyclones, and thunderstorms, all of which result from major air mass differences and produce much of the cloudiness and precipitation over the continent.

A sixth control involves the distribution of air pressure over the continent and adjacent oceans. Pressure patterns vary considerably on a seasonal basis due to the temperature extremes within the continent and the differences between the oceanic and land temperatures. These varying pressure patterns coupled with the other climatic controls bring about widely varying wind and air mass patterns throughout North America.

Typically, warm, moist air from the south meets cold, dry air from the north somewhere over the central United States and this meeting occurs in varying patterns (Court, 1973). These strongly contrasting air masses include the continental Arctic (cold land source), continental Polar (cold ocean), maritime Polar, and the Gulf or Atlantic. The tropical air masses are from abnormally warm seas and are warm, moist, and typically unstable to great heights. Air from the Pacific affects the mountainous western third of the continent and also affects the interaction of the southern and northern air masses.

These incessant movements of air rooted in the six climatic controls of the North American continent provide an exceptional variety of weather extremes on a day-to-day, monthly, seasonal, and annual basis. The variety of weather events produced include droughts, floods, and every known form of severe weather including tornadoes, hail, and ice storms. These extremes alternate with calm periods, either with sunshine or cloudiness. These extremes and nearly continuous weather variations are common in the Lake Michigan region.

CLIMATIC CONTROLS OF THE LAKE MICHIGAN REGION

The climate of the Lake Michigan region is largely dependent upon five climatic controls. Phillips and McCulloch (1972) identified the primary climatic controls of the Great Lakes basin as (*i*) latitude and solar input, (*ii*) topography, (*iii*) weather systems, (*iv*) the lakes, and (*v*) cultural activities.

The major controls of the climate within the Lake Michigan region are the latitude (solar input), the weather systems (air masses and cyclonic storms), and the Lake itself. Topography and cultural effects on climate are of lesser significance, since they are quite localized. Certainly, the continentality, or the great interior location far from moderating influences of the oceans, is the best single-word description of the climate of the region.

Latitude

The position of the earth in relation to the sun basically determines the duration and amount of solar heating of the Lake Michigan region, although cloudiness is an important factor. The four-degree difference in latitude between the northern and southern extremes of the region is reflected in the temperature values presented in Table 1. Both stations are at locales with climates unaffected by the Lake and represent true latitudinal effects. Winter (December-February) temperatures differ by more than 6°C (11°F) and winter precipitation is much heavier in the south. There is less latitudinal difference in summer. Latitudinal variations in temperature are reflected in sizable differences in length of the growing season; it is 60 days shorter in the north than in the south end of the region.

Table 1. Comparison of Temperature, Precipitation, and Growing Season for Stations at the Latitudinal Extremes of the Lake Michigan Region

	Mean Daily Temperature, °C		*Average Precipitation, cm*		
Station Location	*Winter*	*Summer*	*Winter*	*Summer*	*Average Length Growing Season (0°C)*
Valparaiso, Indiana (41°35')	-2.4	22.0	16.2	28.5	170 days
Stambaugh, Michigan (45°48')	-8.7	17.9	9.3	28.0	110 days

Weather Systems

There are two forms of weather systems which have a great influence on the climate: air masses and cyclonic storms. Certainly, a major feature of the climate of the Lake Michigan region is the variety of weather conditions that occur on an almost daily basis as a result of these systems. The settled weather associated with the high-pressure systems is generally ended every few days by the passage of low-pressure systems which typically bring overcast skies and precipitation. Such rapid and marked changes in the weather are common during all four seasons. This reflects the location of the region between the sources of warm, moist air to the south and the cold, dry air to the west and north. The Great Lakes region experiences a variety of air masses that originate from quite distant ocean and land areas. These air masses are often modified by the surface terrain. The predominating air mass is the mild Pacific or maritime Polar (Bryson, 1966).

In winter, the region has many days with clear, dry, sunny weather and temperatures below freezing. Such air originates over the Arctic and has shallow layers of very cold and dry air. This type of winter air mass occurs 20% of the time in winter, and when it passes across the relatively warm water of Lake Michigan a common result is snow storms in the lee of the Lake in Michigan. Air masses originating in the Pacific dominate the winter weather more than 75% of the time. These lose much of their moisture over the Rocky Mountains but still have higher temperatures and humidity than the Arctic air masses. The Pacific air masses arrive from a variety of directions and often produce cool, cloudy weather over the region.

In summer, hot, humid air masses from the Gulf of Mexico affect the region about 40% of the time. Exceptionally high temperatures and humidities, thunderstorms, and high pollution levels are common events in this air. Temperatures in these air masses are often in excess of 27°C (80°F). When these air masses cross Lake Michigan they are cooled from below, and this often creates inversions. Summer air from Pacific sources has a marked effect on the weather of the region. This air, traveling across Canada, arrives in the region relatively cool and dry, bringing bright skies and relief from the haze and pollution typically present with tropical air. Pacific air has a summertime frequency of about 30%. Other summer air masses include hot, dry air from the southwestern United States and cool Arctic air.

The spring and fall seasons are periods of climatic transition. They typically have complex weather patterns with contrasting air masses that induce altered conditions. Their frontal systems move rapidly and often produce extensive cloud cover and continuous rains or showers through the region.

Low pressure systems that originate in western North America cross the continent along various tracks. As these storms move, they often swing to the northeast as they reach the Great Lakes (Phillips and McCulloch, 1972). Most of the cyclonic storms come either from the Alberta region or the central Rocky Mountains, but in summer, roughly 25% of the storms develop in the Great Lakes region. Winter storms may intensify over the lakes as large quantities of heat and moisture are added by the lakes to the atmosphere. On the average, 24 cyclonic storms pass through or near the Lake Michigan region during the winter, whereas only 12 pass in the summer.

The number of days with thunderstorms at a point varies from less than one in winter months to more than ten in the mid-summer months. The greatest annual number, 40 thunderstorm days, occurs in the southern portion of the region because of the higher temperatures and greater frequency of tropical air. The least number of thunderstorms occurs in the northern areas of the region where 20 days are typical. The lakes also greatly affect the occurrence of thunderstorms in their vicinity (Changnon, 1966a), and they exhibit influences on the frequency of severe weather including hailstorms, although the effect on tornadoes is uncertain.

The Great Lakes

The presence of the Great Lakes is one of the major controls affecting the climate of the Lake Michigan region (Visher, 1943). Certain air entering the region is modified by Lake Superior, and Lake Michigan likewise affects the climate over itself and the downwind (eastern) areas in Michigan. The lakes act as a vast reservoir for the storage and exchange of heat energy with the atmosphere, and as such, the lakes moderate the temperature regimes over themselves and adjacent land areas. At most times of the year, the Lake water temperature is quite different from the temperature of the air masses passing over Lake Michigan, so the Lake is either warming or cooling the overlying air constantly. Through evaporation, the Lake also serves as a moisture source for overlying air masses. The lakes tend to extract heat from the overlying air masses when the lakes are cooler during the warmer seasons (spring and summer); this produces stabilization of the air over the water, condensation of moisture from air onto the water surface and reduction of low-level clouds over the lakes, and development of water-to-land wind flow. The reverse is true in the cold seasons (fall and winter) when the lakes become a source of moisture and heat to the atmosphere. The various special lake effects on various weather conditions are described further in a later section of this volume.

Topography

The effects of topographic differences on the climate of the Lake Michigan region are not great and tend to be generally localized to areas of higher elevation. Most of the topography is level or gently rolling country although there is hilly country in the Upper Peninsula and northern Lower Peninsula of Michigan that alters the climate in those locales. Most elevations typically range from 150 to 300 m ($\sim$490 to 980 ft) above mean sea level (msl), although certain locales in the Upper Peninsula reach 600 m ($\sim$1970 ft) msl. These much higher elevations have slightly lower temperatures but typically have little other climatic differences. The topography is not a major climatic control in the Lake Michigan region.

Cultural Effect on Climate

In certain areas of the Lake Michigan region, cultural influences affect the climate. In general, these are minor and are related to their immediate locale. Changes in swamps by drainage and additions of reservoirs produce very local alterations in temperature and humidity. However, the most important cultural climatic alterations have resulted from the cities of Chicago and Milwaukee. Each city has developed a unique climate which is warmer, less humid, windier, and cloudier than surrounding rural areas (Landsberg, 1970). Importantly, Changnon (1968a) has shown that the effects of the Chicago region on the atmosphere have increased the precipitation and severe weather regime significantly up to 50 km (31 mi) downwind of the urban area. The increasing use of Lake Michigan as a source of cooling water used in power production has been estimated to lead to a 1% increase in Lake evaporation (Changnon, 1971).

CLIMATOGRAPHY OF THE LAKE MICHIGAN REGION

Many climatic classifications have been developed to allow regional and continental comparisons. The most famous of these is the Köeppen classification which Ackerman (1941) used to define the climatic regions in North America. The Köeppen climatic classification system is based on mathematical formulas and was the first major quantitative climatic analysis based on the key temperature and precipitation factors that affect vegetative growth. The Lake Michigan region falls within a large area labeled Dfb, a type classed as humid continental. The Dfb climate class means that the coldest month at all points is under -3°C (27°F), there is no dry season, there is little difference in average monthly precipitation amounts, and the warmest month of the year is under 22°C (72°F) but four months have mean temperatures over 10°C (50°F). The Dfb climate encompasses all of the Great Lakes and is found in only two other sizable areas of the world, eastern Europe and central China.

Five unique features of the climate of the Lake Michigan region are:

1. Four distinct seasons.
2. Major temperature contrasts over only 600 km (373 mi) latitude.
3. An extreme variety of precipitation types and amounts with little monthly average variation.
4. Extreme variability of weather conditions between areas and between years.
5. The effect of Lake Michigan in air mass modification.

The north-to-south latitudinal differences in temperature are greater in winter than in summer by about 3°C (5.4°F) (Table 1). The Lake Michigan region has warm summers with frequent periods of hot and humid air. Polar air masses dominate in winter with average temperatures below freezing for three months in the south and five months in the north. The transitional seasons, fall and spring, experience high frequencies of storm passages and variable weather conditions. However, the fall season has a smaller number leading to many warm and pleasant sunny days.

The annual average precipitation varies between 71 cm (28 in.) in the north to more than 90 cm (35 in.) in the south of the region with quite even distribution throughout the year, although there is somewhat greater precipitation during the growing season. Droughts occur occasionally, but are usually of short duration. The flood frequency in the region is relatively low, with most occurring in the late winter or early spring as a result of sudden warming and rain combined with the snow melt. Snowfall variation over the region is great, ranging from annual totals of 40 m (∿130 ft) in the high country of the Upper Peninsula of Michigan to less than a meter in the extreme southwest (Chicago). Areas downwind of the Lake in lower Michigan receive sizable amounts of snowfall due to lake-induced storms in the early winter.

An interesting feature of the regional climate is the great variety of weather events and their magnitude between seasons and years, a condition partially induced by Lake Michigan. The quasi-marine climate induced in western lower Michigan produces considerable geographical differences in temperature and length of growing season. Extremely low temperatures of -40°C (-40°F) have been recorded in the northern-most area, whereas record low values have never fallen below -30°C (-22°F) in the south.

The prevailing wind is from the southwest over the southern half of the Lake Michigan region and is more westerly over the northern sections. However, winds come from every direction and vary considerably with the frequent passages of cyclonic systems typical of this climate.

LAKE EFFECTS ON WEATHER AND CLIMATE

Lake Michigan and the other Great Lakes produce some unique weather alterations and they modify practically all climatic conditions. Knowledge of the lake-induced climate is critical to an understanding of the region's climate and deserves a special description. Most lake-weather studies have pertained to Lake Michigan because of its better data base, but the climatology of lake-effect weather is considerably hampered by a lack of long-term collection of weather data, particularly over the lakes. Certain weather changes produced by Lake Michigan are discussed to illustrate average changes over the Lake and in the downwind shore area in Michigan (Changnon and Jones, 1972).

The Lake modifies the large-scale circulation field. In general, it acts to strengthen passing low centers in winter and to develop high-pressure centers in summer (Cox, 1917). The lake-related mesoscale modifications include (*i*) transfer of heat and moisture so that the Lake frequently induces distinct air mass modifications, and (*ii*) changes in air motion due to frictional and thermal gradient effects. The vertical extent of moisture and heat transfer in the cold season often extends to 2.5 km (1.6 mi) (Willett, 1933), although it is much less in summer. Variations in air motions due to land-lake differences in frictional effects (from air going from a smooth lake to rough land) result in shoreline convergence zones (George, 1940). In summer, the relatively cool Lake produces a low-level air mass modification resulting in cold domes of air with their tops from 100 to 150 m (∿330 to 490 ft) above the lake surface (Lyons, 1970). When the flow pattern is not disturbed by a lake-breeze circulation and when the gradient flow is 16 km/hr (10 mi/hr) or more, advection of warm air across the lakeshore occurs, and a strong inversion develops between the cold dome of air near the lake surface and the warmer air above. This inversion may persist downwind of the Lake until surface roughness and surface heating are sufficient to overcome it. In general, a lake breeze exists somewhere around Lake Michigan on approximately 50% of the summer days.

The climatology of lake-related increases or decreases in clouds and precipitation is hindered because of the great difficulty in obtaining measurements over the lakes. Lake-related snow increases occur in late fall and winter downwind of the unfrozen Lake (Eichenlaub, 1970). In these cases, the water is relatively warmer than the overlying air, and moisture, supplied by evaporation into colder, dryer air masses, is condensed as arctic sea smoke or clouds which may grow sufficiently to form snow showers. These showers often intensify as they pass from the Lake to shore. Evaporation from the Lake is greatest during the late fall and early winter when the greatest vapor pressure difference exists between the water and the air. Lake-effect snowfalls account for 30-50% of the total snowfall in the major lake snowbelt which parallels the eastern shore (Muller, 1966).

The ability of the lakes to increase or decrease cloudiness is an important lake effect. Figure 2 is an example of the summer dissipation of clouds over Lake Michigan by the cool Lake which is restricting overlake convection. Of course, an increase in cloudiness occurs in fall when the Lake is often warmer than the air. There is a sizable increase in average cloudiness because of the Lake (Fig. 3). These alterations in cloudiness result in changes in sunshine and radiation.

Fig. 2.

Satellite Photograph Illustrating Effect of Lake Michigan on Summer Cloud Cover.

The amount and frequency of precipitation over and downwind of the lakes is also affected considerably by the lakes. Several studies of overlake precipitation using island raingage data and radar data (Hunt, 1959; Blust and DeCooke, 1960; Changnon, 1968b) have shown that lake rainfall, as compared with land basin rainfall, is generally diminished in the summer (when the cooler lakes act to stabilize conditions) and increased in the winter and fall (when the lakes add moisture and heat to enhance overlake instability). Figure 4 depicts the percent changes in the average annual precipitation pattern over the Lake Michigan region due to lake effects (Changnon, 1968b). It shows lake values of 6% less than that over its surrounding watershed and increases of 20% over land. Figure 5 depicts east-west profiles of the average precipitation change across Lake Michigan. Summer decreases are on the order of 10 to 20% over the entire eastern half of Lake Michigan, and cold-season increases of the same magnitude occur but begin farther east.

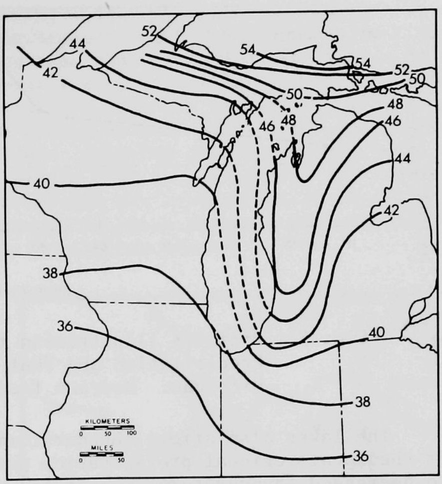


Fig. 3.

Mean Number of Cloudy Days in Fall (September-November). Redrawn from Changnon (1968b).

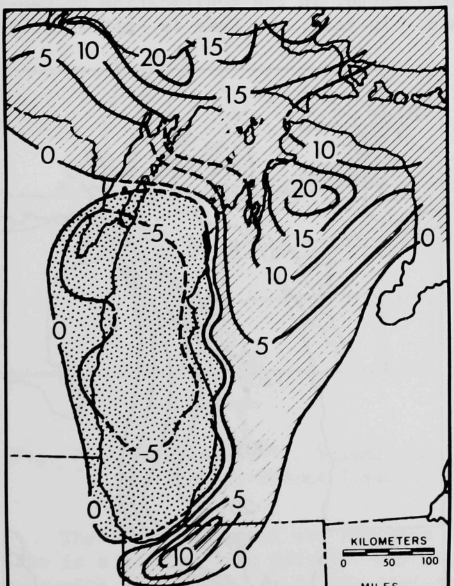


Fig. 4.

Alterations in Average Annual Precipitation, %, Because of Lake Michigan. Redrawn from Changnon (1968b).

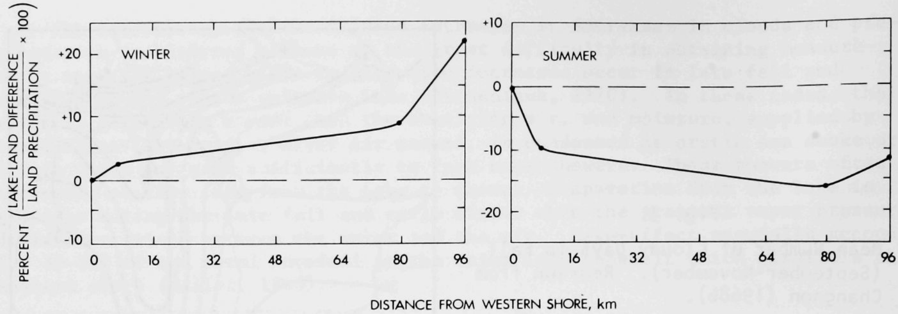


Fig. 5. Profiles Illustrating the Difference between Average Lake Precipitation and That Along the Western Shore of Lake Michigan. Redrawn from Changnon (1968b).

The lakes also affect thunderstorms. Thunderstorms account for 40 to 45% of the total regional precipitation per year. Lake conditions in summer lead to decreased thunderstorm frequencies over and downwind of the Lake (Changnon, 1966a). Thunderstorms are greatly enhanced in fall (Fig. 6) when the Lake is a moisture and heat source.

The lag in the warming and cooling rate of the water surface, in relation to the adjacent land, is the most critical factor in the modification of temperature and the general regional climate. In fact, the Lake is sufficiently

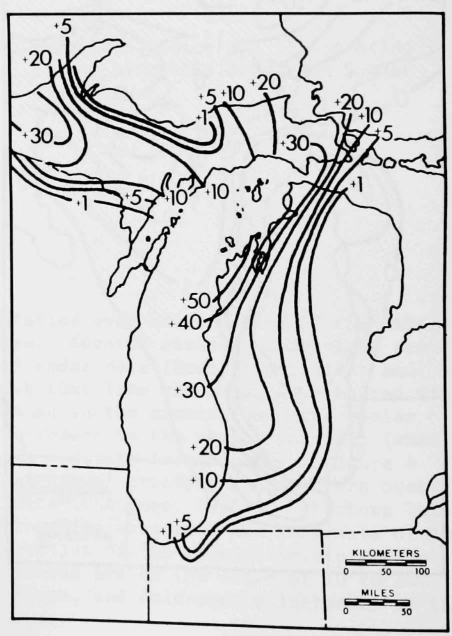


Fig. 6.

Lake-Produced Increases in Fall Thunderstorms as a Percent of the Total. Redrawn from Changnon (1968b).

large to simulate a marine climate on nearby land surfaces. For example, the cold Lake delays the start of the growing season in the spring, but also delays the first frost in the fall. The average lake water temperatures (Millar, 1952) and the mean maximum air temperatures for fall show that the water temperatures are cooler by 1 to 3°C (1.8 to 5.4°F) than the daily maxima (Fig. 7a). However, the lake water temperatures are from 6 to 10°C (11 to 18°F) warmer than the minimum air temperatures (Fig. 7b). Upon the arrival of cold air masses in the fall and winter, the heat of the Lake is released to the overlying air through both sensible heat and through the evaporation of the Lake waters. Mean minimum temperatures in January increase eastward across Lake Michigan; they are 5°C (9.0°F) higher on the eastern shore.

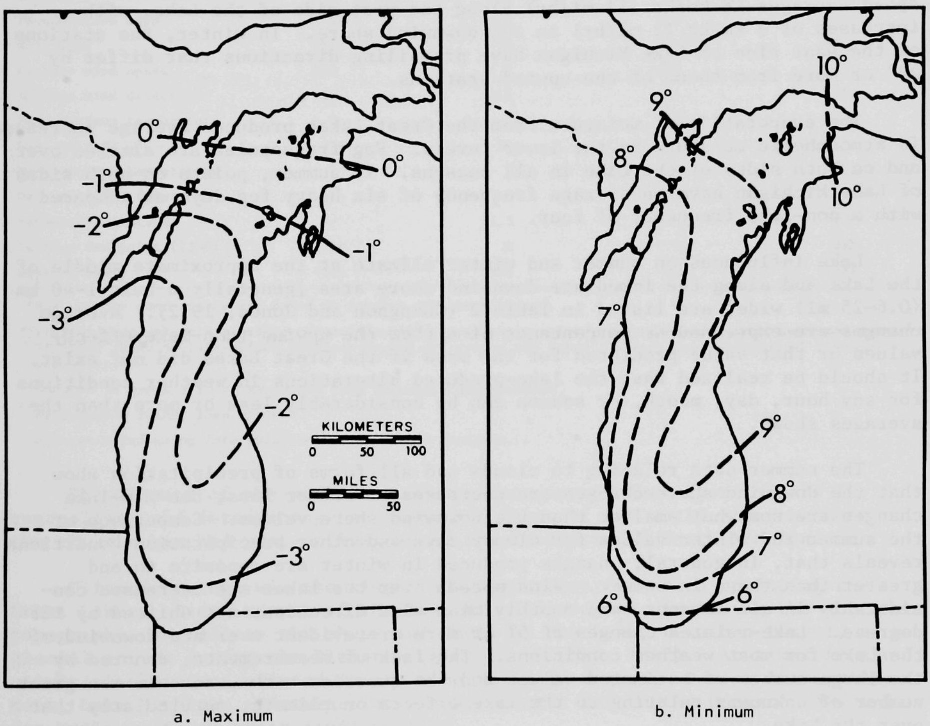


Fig. 7. Differences, °C, between Fall Mean Water Temperature (Lake Michigan) and No-Lake-Effect (Upwind) Air Temperatures.

The modification of the extremes of temperature over and downwind of the Lake is a general lake effect. For example, the average number of days per year with 32°C (90°F) or higher temperatures is eight days west of central Lake Michigan but only four days on the downwind (east) shore. Conversely, the upwind (west) frequency of days with temperatures below 0°C (32°F) is 87, compared with an average of only 83 days on the east side. The patterns of the thermal influences by Lake Michigan are generally symmetrical with the lake shape, but are somewhat distorted eastward (Kopec, 1967).

Lake Michigan affects winds and low-level circulation fields. The land-lake changes in surface frictional characteristics result in increased wind velocities and wind direction changes approaching the gradient winds over the Lake, and then a tendency for a piling up of air on the downwind shore. Lyons and Wilson (1968) and Lyons (1970) have described the formation of convergence zones downwind of Lake Michigan and the frequent development of lake-breeze circulations extending from the shoreline inland, sometimes to distances of 50 km (31 mi). West-to-east differences in average surface wind speeds exist all along the north-south extent of Lake Michigan. In winter, the mean monthly speed averages 18 km/hr (11 mi/hr) along the west side of the Lake, with increases of 3 km/hr (2 mi/hr) on the downwind shore. In winter, the stations on the east side of Lake Michigan have prevailing directions that differ by 20° or more from those of the upwind stations.

The evaporation of moisture from the Great Lakes produces average increases in atmospheric moisture in the lower levels. Fog frequencies are altered over and on both sides of the Lake in all seasons. In summer, points on both sides of Lake Michigan have an average frequency of six heavy fog days as compared with a non-lake frequency of four.

Lake influences on summer and winter climate at the approximate middle of the Lake and along the immediate downwind shore area [generally a belt 1-40 km (0.6-25 mi) wide] are listed in Table 2 (Changnon and Jones, 1972). Average changes are expressed as percentages of either the upwind (non-lake-effect) values or that value predicted for the area if the Great Lakes did not exist. It should be realized that the lake-produced alterations in weather conditions for any hour, day, month, or season can be considerably less or more than the averages shown.

The summer data relating to clouds and all forms of precipitation show that the downwind shore changes are decreases of 15% or less; the mid-lake changes are somewhat smaller than the downwind shore values. Comparison of the summer and winter values for cloudy days and other precipitation conditions reveals that, in general, changes produced in winter are opposite to and greater than those in summer. Wind speeds over the lakes are increased considerably in all seasons, and monthly mean wind directions are shifted by ±25 degrees. Lake-related changes of 5% or more are evident over and downwind of the Lake for most weather conditions. The lack of measurements, denoted by the large number of estimated values and the question marks, reveals the great number of unknowns relating to the lake effects on climate, particularly that over the Lake.

HISTORICAL PERSPECTIVE

The climate of the world is always changing but the rate of change fluctuates (Changnon, 1975). We are currently in one of the warmest periods in the past 100,000 years (U. S. Natl. Acad. Sci., 1974); it is 4 to 6°C (7 to 11°F) warmer than in times of maximum glacial extent. The great variability of weather and its obvious effect on our crops and fuel bills makes it easy to realize that long-term climatic changes can produce significant effects.

Table 2. Percentage Difference* between Actual and Predicted** Weather Conditions at Typical Mid-Lake Location and at Downwind Shoreline Location (Modified from Changnon and Jones, 1972)

	Summer (June-August)		*Winter (December-February)*	
Weather Conditions	*Mid-Lake*	*Downwind Shore*†	*Mid-Lake*	*Downwind Shore*†
Cloudy days	-10e	-15	+20e	+35
Solar radiation	+21	?	-10	?
Percent possible sunshine	>+ 5e	+ 5	-10e	-30
Snowfall	--	--	+ 3	+50
Precipitation	-15	-10	+ 7	+25
Days with ≥ 0.01 inch	- 7	-11	+17	+45
Thunderstorm days	± 5e	±10	+10††	+25††
Hail days	-15e	-33	+25††	+100
Surface wind speed	+30	± 5	+98	+11
Surface wind direction	±25	±14	±14	±>12
Mean maximum temperature	- 9	- 3	+ 3e	+ 6
Days of ≥ 32.2°C	-37e	-50	--	--
Mean minimum temperature	± 1	- 2	+10e	+15
Days of ≤ 0°C (minimum)	--	--	-3e	- 6
Evapotranspiration	--	± 3	--	+37
Surface dew point (1300)	0e	0	+ 9e	+12
Days of heavy fog	+70e	+50	-16e	-28

**Most of the comparisons are based on studies of Lake Michigan.*

***Predicted values determined by comparison with upwind shore values or by comparison with patterns constructed using no-lake-effect stations beyond and around the lakes (latitudinal-longitudinal isanomal analysis).*

†Located in areas 1 to 40 km inland from lakeshore and downwind.

††Fall season rather than winter.

e = estimated using interpolations from pattern analysis.

The climate of the world has always been one of the major factors in controlling and determining the flora and fauna of the world. Furthermore, the climate has had vast influences on the landforms of North America.

Climatic change was the single most important factor in producing the Great Lakes. Every aspect of the Lake Michigan region, including the surface topography, as well as the shape and depth of the Lake, resulted largely from glacial action during the Pleistocene Epoch (Hussey, 1947). At times Arctic climatic conditions existed in the Lake Michigan region. During its development, Lake Michigan underwent three major phases before the present Lake and its basin achieved their configuration.

LAKE CHICAGO--PHASE I

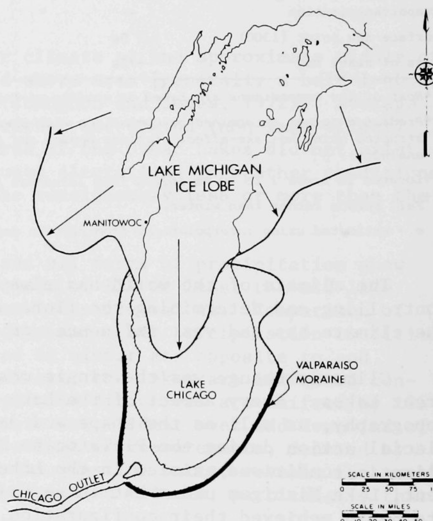
The basins of the modern Great Lakes were once broad lowlands, long before the Pleistocene Epoch. The Pleistocene Epoch is estimated to have lasted from 1 to 2 million years. It was composed of four glacial and three interglacial stages, all produced by major climatic fluctuations extending over thousands of years. Basically, the glacial stages were of short duration and the interglacial periods were relatively long. The most recent of the four glacial stages was the Wisconsin Stage. It was the primary stage for the formation of the Great Lakes, as we know them, and this stage lasted from 10,000 to 50,000 years. It should be realized that the Wisconsin Stage was composed of 7 substages (Hough, 1958), and each of these substages was produced by climatic shifts that led to major oscillations of the ice in the Lake Michigan region.

One of these, the Cary Substage, was a critical period for shaping the Lake Michigan region. It left a major morainic system called the Valparaiso, which still marks the southern rim of the Lake Michigan basin, and a series of other concentric morainic systems throughout the Lake Michigan region. The present land area of the Lake Michigan region is composed of a series of low moraines separated by intermorainal till plains all resulting from various oscillations of the glaciers of the Wisconsin Stage.

In the warming period of the Cary Substage, the southern border of the glacial ice sheet near Chicago began to melt. The front of the great ice sheet slowly retreated over the area that is now northern Illinois, southern Wisconsin, and central lower Michigan. The portions of the glacier that filled the deep scoured valley (that was to become Lake Michigan) were extremely thick and formed a great lobe of ice when the thinner ice to either side melted (Fig. 8).

Fig. 8.

Lake Chicago, the First Major Lake Stage, and the Lake Michigan Ice Lobe during One of the Glacial Retreats Produced by a Temporary Warming Period of the Mid-Wisconsin Stage.



While the front of the great ice lobe receded unevenly, enormous volumes of meltwater collected in the valley as it was gradually uncovered. Thus, Lake Michigan slowly came into existence as did the other Great Lakes. Lake Chicago occupied the southern end of the present Lake Michigan (Fig. 8) with the Lake Michigan ice lobe of the Wisconsin glacier still occupying much of the upper lake area. Since the ice generally blocked the St. Lawrence region, Lake Chicago drained through a low area in the Valparaiso moraine and into the Mississippi River through the Chicago outlet (Fig. 8). Heavy drainage through what was to become the Illinois River was responsible for producing the large size of the current valley. When the Wisconsin ice lobe stood in the middle of the Lake Michigan basin (Fig. 8), oak and spruce trees were growing in the Chicago-Benton Harbor area. Since vertebrate life was abundant and red deer and other animals were present at the south end of Lake Michigan (Lake Chicago), the climate could not have been especially severe. Lake Chicago appeared and disappeared six times in the Wisconsin Stage as the climate and glacial extent shifted.

A profile of soil deposits near Manitowoc, Wisconsin (Hough, 1958) revealed an interesting series of events illustrative of how the climatic shifts affected the geology and landforms of the Lake Michigan region during late substages of the Wisconsin Stage. The sequence of these deposits (Fig. 9), beginning at the bottom (earliest time), suggests the following series of events:

1. Expanding glacial ice from the north deposited gray till.
2. A warmer climate caused retreat of the ice from this locality and Lake Chicago flooded the area, depositing clays, silt, and sand.

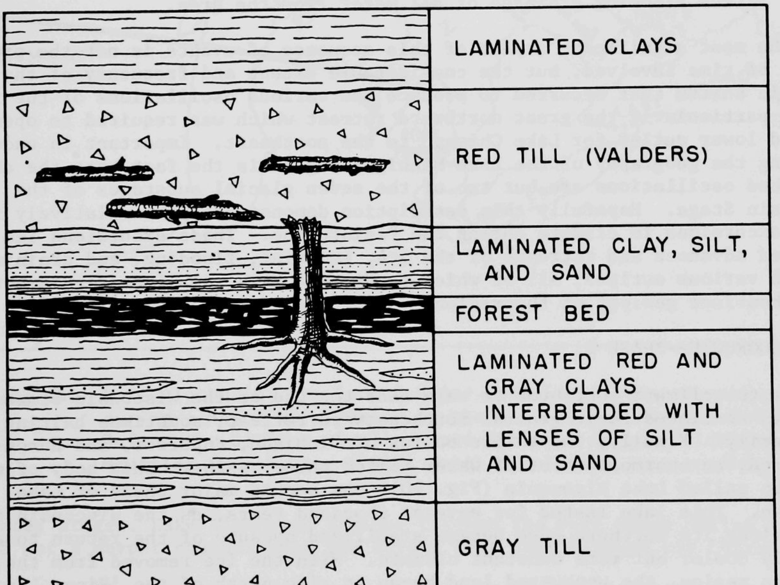


Fig. 9. A Profile of Deposits near Manitowoc, Wisconsin, Which Defines the Climatic Oscillations of Two of the Seven Glacial Substages of the Wisconsin Stage (Hough, 1958) (with permission, see credits).

3. Considerable additional warming caused drainage of the lake; the retreat of the ice front to the north opened a new and lower outlet, probably near the Straits of Mackinac, which allowed a forest to grow.

4. A shift to a colder climate caused the advance of an ice front, which closed the northern lake outlet, and rising lake water levels produced flooding so that sands and other materials were deposited over the forest.

5. A rapidly cooling climate in the flooded area resulted in a rapid advance of ice, which broke off trees (laying them in a southwesterly direction) and deposited red glacial till.

6. A warming climate melted the ice, and lake water again flooded the area (draining through the Chicago outlet) and deposited laminated clays.

7. Continued warming caused the ice front to retreat farther northward and this uncovered a lower northern outlet near Mackinac, thus allowing drainage of all water from the area.

The most significant aspect of this sequence of events is not the probable length of time involved, but the considerable extent and frequency of the climatic shifts that occurred to produce the various oscillations of the ice front, particularly the great northward retreat which was required to open a new and lower outlet for Lake Chicago to the northeast. Important in understanding the geography of the Lake Michigan region is the fact that the above-described oscillations are but two of the seven glacial substages of the Wisconsin Stage. Hopefully this description demonstrates the relatively frequent excursions in climate during the Pleistocene. These excursions led to repeated advances and retreats of the ice, scouring, flooding, and draining through various outlets, all of which produced a very complicated physiography and subsurface geology of the region.

LAKE ALGONQUIN--PHASE 2

As the climate continued to warm near the end of the Wisconsin Stage, the glaciers continued their general northeastward retreat, sometimes halting temporarily. Finally, the entire basins of Michigan, Superior, and Huron were uncovered; an enormous sheet of water filled these basins. This body of water has been called Lake Algonquin (Fig. 10), the second major phase of Lake Michigan. This lake lasted for several thousand years, as the Wisconsin ice front along its northern edge became stabilized because of the return to a slightly cooler but more constant climate. With the ice removed from the Lake Michigan region, the uncovered land began to rise north of the 'Hinge Line' (Fig. 10). The existence of Lake Algonquin is still reflected in many of Lake Michigan's former beaches (sandy plains) found around the Lake. In the south they are at about the same locale as the present lake beaches, but they are at much higher elevations in the northern half of the region where the uplift puts them 80 m ($\sim$260 ft) above current lake levels.

This gradual upwarping in the northern portions of the Great Lakes basin eventually closed certain outlets and led to the demise of Lake Algonquin. In

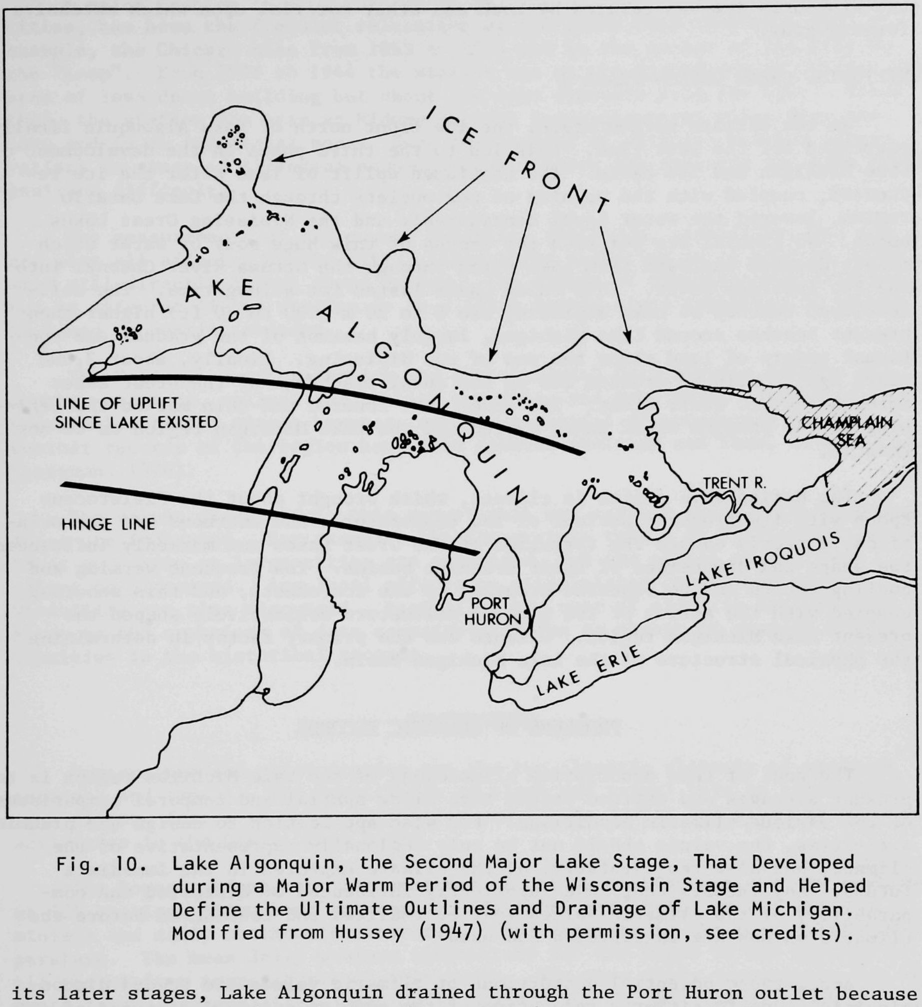


Fig. 10. Lake Algonquin, the Second Major Lake Stage, That Developed during a Major Warm Period of the Wisconsin Stage and Helped Define the Ultimate Outlines and Drainage of Lake Michigan. Modified from Hussey (1947) (with permission, see credits).

its later stages, Lake Algonquin drained through the Port Huron outlet because it had cut a deeper channel than the stream that went through the Chicago outlet.

In the hundreds of years during the time of Lake Algonquin, the land immediately south of the ice front, including the northern part of the current Lake Michigan region, was either covered with water or was quite barren. However, the land a few hundred kilometers farther south was not barren. Shells of certain clams are found along the Algonquin beaches near Chicago and they certainly could not have survived under Arctic climatic conditions. The flora and fauna of the Chicago area during the Lake Algonquin period suggest that the climate of the southern Lake Michigan area was similar to the climate now found along northern Lake Superior. It is even possible that the stagnant edge of the Wisconsin ice was covered by rock and other material upon which extensive forests grew.

NIPISSING GREAT LAKES--PHASE 3

As the climate warmed again, the ice front north of Lake Algonquin finally retreated for the last time. This led to the third phase in the development of Lake Michigan and its basin. The continued uplift of land after the ice retreated, coupled with the opening of new outlets through the Lake Ontario region, lowered the water level considerably and the Nipissing Great Lakes began. No glacial ice bordered the shores of this huge body of water which mainly drained eastward from Lake Huron through the Ottawa River Channel into the St. Lawrence River. This third phase lasted for a long time. The well-developed beaches of Lake Nipissing are 8 to 20 m ($\sim$30 to 70 ft) higher than present beaches around Lake Michigan, largely because of the gradual and continual upwarp of land since the end of the Nipissing. Finally, about 3,000 years ago, continued erosion led to the total discharge of the Great Lakes through the St. Clair River. The lakes were lowered and this marked the beginning of the present Great Lakes system and the Lake Michigan region as we now know it.

The hemispheric shifts in climate, which brought about the Pleistocene Epoch with its frequent periods of low temperatures and enormous ice accumulations, directly caused the formation of the Great Lakes and markedly influenced the shape and dimensions of their drainage basins. The frequent warming and cooling cycles led to repeated scouring by the ice sheets, and this scouring coupled with the action of the glacial meltwaters collectively shaped the present Lake Michigan region. Climate was the primary factor in determining the physical structure of the Lake Michigan Basin.

PROBLEMS OF CLIMATIC RECORDS

The goal of this descriptive climatology of the Lake Michigan region is to present averages and extreme values that allow spatial and temporal comparisons of the various climatic conditions. For wise application to design and planning activities, the values should not be only regionally representative of the climate, but also representative of the climate expected in the immediate future. Any factors that have incorrectly influenced or distorted the comparability of the climatic values must be realized and considered before the climatic values are interpreted and used.

Among these potential distortions of climatic values are record discontinuities, due to either a relocation of the station during its period of service or to a change in the site at one location. The exposure of certain weather instruments, particularly raingages and locales where snow is measured, can alter the true values. Raingages shielded by buildings and trees will catch 5 to 10% more precipitation than those in open fields. A weather shelter with thermometers located in or near a wooded area will measure lesser temperature extremes than those measured in a nearby shelter in an open field. A wind instrument at an open airport will sample higher wind speeds than one inside a small town or city where it is more sheltered.

A major problem in some locales in the region, particularly in the major cities, has been the frequent relocation of the prime data station. For example, the Chicago site from 1863 to 1925 was in the center of the city or the "Loop". From 1926 to 1944 the station was at the University of Chicago, an area of less dense building but about the same distance from the Lake. Since 1945, the station has been at Midway Airport located several miles from the Lake and in an industrial zone. Such relocations of official weather observations to areas of different meso-climates distort the averages and make trend analyses difficult.

The measurements of sky cover, sunshine, radiation, visibility, and fog are also all affected by the site. Atmospheric pollution in or near an urban area will directly affect these values. The number of thunderstorms reported can be affected if the station is in a noisy locale since reporting of storms is based on hearing thunder.

The National Weather Service and Environmental Data Service operate the weather stations, collect and publish the data, and make major efforts to get comparable station sites; however, certain potential discrepancies in the weather records of the region have been debated (Holzman and Thom, 1970; Changnon, 1970).

The values presented in this report that may reflect local site peculiarities are indicated. For example, the temperature trends of stations at small towns and those at large cities are separated, and the effect on the mean values is discussed. Any local effects on site-related conditions such as visibility are also discussed. Basically, the user of climatic data must be alert to the questions of data comparability due to abrupt or gradual discontinuities in the historical records.

TEMPERATURE

Temperature and precipitation are the two climatic elements of greatest interest and impact. The sensitivity of plant and animal life to temperature is a primary factor in human activities and in the design and planning of many activities in the Great Lakes basin.

The lowest and highest temperatures occurring within each day are measured at 125 stations throughout the region, and these are listed as the daily minimum and daily maximum temperatures. Their average is the mean daily temperature. The mean daily maximum temperature for any month is the average of all the maximum temperatures of that month. The mean daily temperature for the month is the average of the mean daily maximum and the mean daily minimum values for any month, and the mean annual temperature is the average of these 12 monthly temperatures.

The strong continentality of the climate has produced some extremely high and low temperatures, although the Lake modifies the continentality (Kopec, 1965). The highest temperature ever recorded at any weather station in the Lake Michigan region was 46°C (115°F) in northern Indiana, and daily temperatures in excess of 43°C (109°F) have been measured in the Upper Peninsula of Michigan. The lowest temperature on record in the region is -45°C (-49°F), recorded at Humbold, Michigan.

Surface air temperatures are traditionally measured using glass mercury thermometers. One thermometer is designed to record the maximum temperature, a second records the minimum, and once per day observations (and resetting) of these thermometers yields the daily high and low values. These thermometers are mounted in a wooden louvered shelter located above a grass surface with the thermometers at 1.4 m (4.5 ft). At the eight National Weather Service first-order stations in the region, which are operated continuously, air temperatures are recorded continuously on devices called thermographs. Temperature data utilized in this section have come from a variety of sources, but the average and extreme values are based on data from 1931 to 1965, unless noted otherwise.

The relationship of the surface air temperature values measured 1.4 m (4.5 ft) above ground to the air temperatures very near ground and soil temperatures just beneath the ground are revealed in Table 3. Baker (1968) collected temperature data at 10 cm (4 in.) above ground and 1 cm (0.4 in.) below ground under both sod and bare soil in southeastern Minnesota where conditions are representative of the Lake Michigan area. Air temperatures near the

Table 3. Relationship of Average Air Temperatures (°C) Measured in Standard Shelters (1.4 m above Ground) to Temperatures Measured near and below Ground (Data from Baker, 1968)

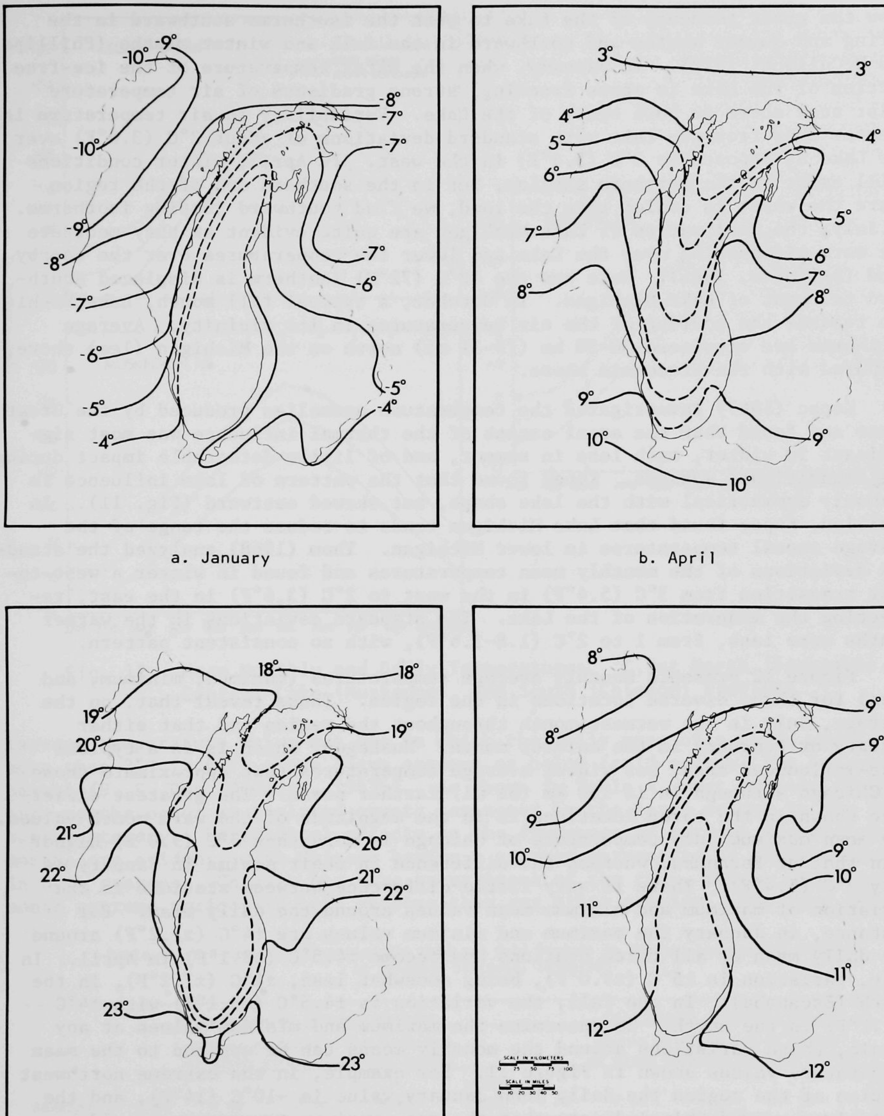
	Difference from Shelter Air Temperature		
		In Soil, 1 cm under Ground	
Season	*In Air, 10 cm above Ground*	*Sod Cover*	*Bare Surface*
Winter	-1	+8	+8
Spring	-2	+1	+2
Summer	-3	+2	+4
Fall	-3	+1	+2

ground were 1 to 3°C (1.8 to 5.4°F) lower than those at shelter height. Temperatures 1 cm below the soil were consistently warmer than shelter average temperatures. The greatest difference occurred in the winter season, when the soil is frequently shielded by snow cover. There was also a greater difference between air and bare soil temperatures than between air and sod-covered soil temperatures. Other studies of soil temperatures in the region (Moses and Bogner, 1967) have shown that summer and winter soil temperatures at deeper levels are much more moderate than the air temperatures, and soil maxima and minima typically lag air temperature seasonal extremes by one month at depths greater than 30 cm (12 in.).

MONTHLY AND SEASONAL AVERAGES

The temperature pattern of the region would be strongly latitudinal except for the presence of the Lake which tends to distort temperature values on the east side of the Lake. The annual average temperatures range from nearly 16°C (61°F) in the south end of the region to 5°C (41°F) in the north. However, it is important to realize that there is considerable year-to-year variability between monthly and seasonal temperatures in the Lake Michigan region.

Monthly mean temperature patterns appear in Figure 11. The patterns over the Lake have been estimated from isolated island and ship data, and they all



a. January

b. April

c. July

d. October

Fig. 11. Average Monthly Temperature Patterns, °C.

show the great tendency of the Lake to push the isotherms southward in the spring and summer months and northward in the fall and winter months (Phillips and McCulloch, 1972). In January, when the water temperature of the ice-free portion of the Lake is above freezing, strong gradients of air temperature exist near shore on both sides of the Lake. Variability in air temperature is greater away from the Lake with standard deviations of about 2°C (3.6°F) over the Lake as opposed to 3°C (5.4°F) in the west. In April, winter conditions still exist in the northern section, but in the southern end of the region where the water is cooler than the land, we find southward jutting isotherms. In July, the cool waters of Lake Michigan are quite evident as they moderate the warm air passing over the Lake and lower the temperatures over the nearby land (Bellaire, 1965). Note how the 22°C (72°F) isotherm is displaced southward far east of Lake Michigan. In October, a typical fall month, Lake Michigan retards the cooling of the air temperatures in its vicinity. Average isotherms are displaced 30-50 km (19-31 mi) north on the Michigan (lee) shore, compared with the Wisconsin shore.

Kopec (1967) investigated the temperature anomalies produced by the Great Lakes and found that the areal extent of the thermal influence was most significant in winter, much less in summer, and of little detectable impact during the transitional seasons. Kopec found that the pattern of lake influence is commonly symmetrical with the lake shape, but skewed eastward (Fig. 11). In addition, Kopec found that Lake Michigan tends to reduce the range of the average annual temperatures in lower Michigan. Thom (1968) analyzed the standard deviations of the monthly mean temperatures and found in winter a west-to-east transition from 3°C (5.4°F) in the west to 2°C (3.6°F) in the east, reflecting the moderation of the Lake. The standard deviations in the warmer months were less, from 1 to 2°C (1.8-3.6°F), with no consistent pattern.

Figure 12 presents monthly average temperatures (maximum, minimum, and mean) for three diverse locations in the region. These reveal that, on the average, July is the warmest month throughout the region and that either January or February is the coldest month. Muskegon, which is in a typical lake-influenced area, has winter average temperatures that approximate those at Chicago although it is 130 km (81 mi) farther north. The greatest difference shown in the three locations is in the magnitude of the warm month values. The mean maximum July temperature of Chicago is more than 5°C (9.0°F) higher than that at Escanaba, whereas the difference in their maxima in January is only 3°C (5.4°F). There is very little difference between stations in the variation of maximum and minimum mean values around the daily mean. For instance, in January the maximum and minimum values are ±4°C (±7.2°F) around the daily mean at all three stations and become ±4.5°C (±8.1°F) in April. In July, variation is ±5°C (±9.0°F), being somewhat less, ±4°C (±7.2°F), in the north (Escanaba). In the fall, the variation is ±4.5°C (±8.1°F) with ±4°C (±7.2°F) in the north. To determine the maximum and minimum values at any locale, these variations around the monthly means can be applied to the mean temperature values shown in Figure 11. For example, in the extreme northwest portion of the region the daily mean January value is -10°C (14°F), and the variations around this indicate that the mean maximum temperature would be -6°C (21°F) and the mean minimum -14°C (7°F).

FREQUENCY OF EXCEPTIONALLY WARM AND COLD MONTHS

A major factor in the operations of the construction industry and power plants in the region relates to prolonged periods of extreme temperatures. An

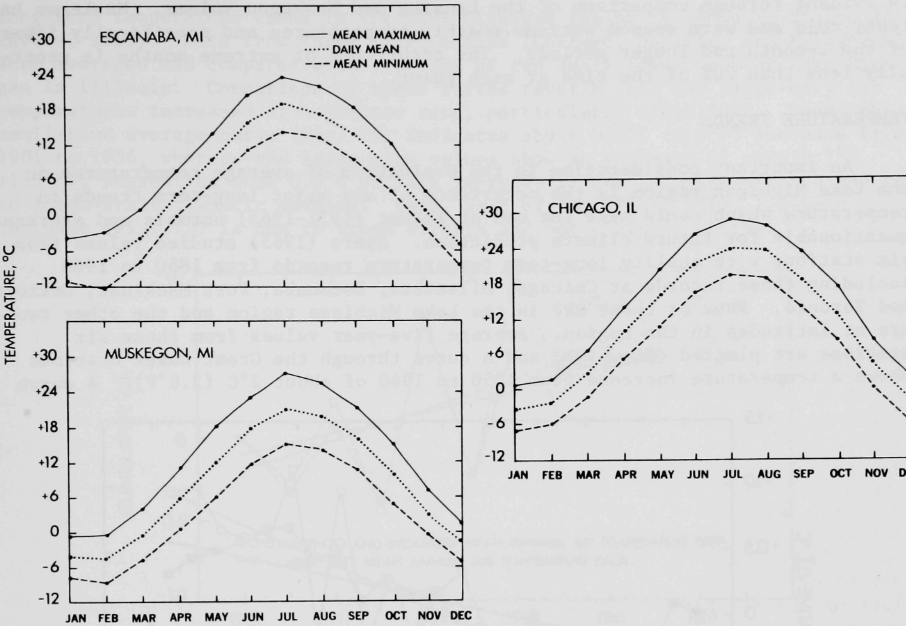


Fig. 12. Mean Monthly and Daily Temperatures, °C, at North (Escanaba), Central-Lake (Muskegon), and South (Chicago) Stations.

extreme temperature value was one in which the daily mean of a given month was more than 2°C (3.6°F) above (warm season) or below (cold season) the long-term normal (U. S. Dep. Commer., 1963b). As shown in Table 4, most extreme temperature months occur as isolated events, as noted by the large values in the one-month category. Latitudinal effects on the frequency of extreme temperature months are evident, with Chicago having a greater percentage of extreme months in both seasons. Chicago has more occurrences of the two-, three-, and four-month extreme periods in both seasons than any other station. The lake effect

Table 4. Frequency of Exceptionally Warm and Cold Periods in Heating and Cooling Seasons at Selected Stations, 1930-1965

	Warm Season (June-September)					*Cold Season (December-March)*				
	Number of Times a Hot Period of given duration occurs, months*					*Number of Times a Cold Period* of given duration occurs, months*				
Station	*1 mo*	*2 mo*	*3 mo*	*4 mo*	*% of total*	*1 mo*	*2 mo*	*3 mo*	*4 mo*	*% of total*
Green Bay	18	4	0	1	16	18	4	1	1	17
Muskegon	14	2	0	0	11	13	7	0	0	14
Lansing	19	3	1	0	16	17	5	2	0	17
Chicago	15	9	1	1	18	21	5	3	0	21

**Hot or cold period defined when monthly mean temperature deviates ≥2°C from normal.*

is evident through comparison of the Lansing and Muskegon values. Muskegon has fewer cold and warm season extreme monthly temperatures and specifically fewer of the 2-month and longer periods. The occurrence of extreme months is generally less than 20% of the time at each point.

TEMPERATURE TRENDS

An important consideration in the evaluation of average temperatures in the Lake Michigan region is the occurrence of any major long-term trends in temperature which could make the use of recent (1931-1965) normals and averages questionable for future climate prediction. Ayers (1965) studied values from six stations with quality long-term temperature records from 1850 to 1960 including those records at Chicago, Milwaukee, Escanaba, Fort Mackinac, Detroit, and Toronto. Four of these are in the Lake Michigan region and the other two are at latitudes in the region. Average five-year values from these six stations are plotted (Fig. 13), and a curve through the Great Lakes Stations shows a temperature increase from 1850 to 1960 of about 2°C (3.6°F). A curve

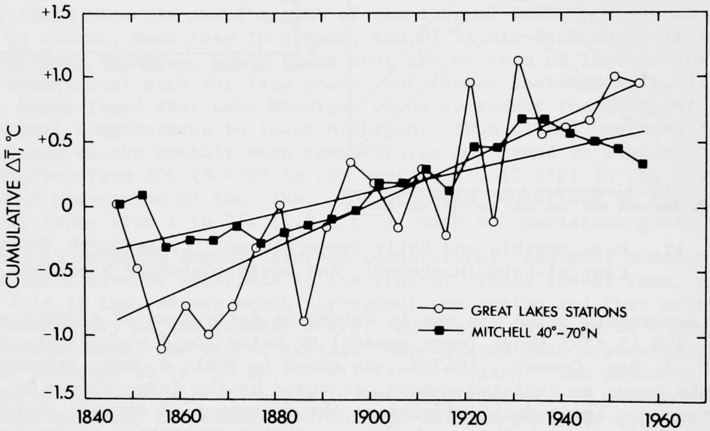


Fig. 13. Trends of Air Temperature in the Great Lakes Basin and the 40° N to 70° N Latitude Zone. Modified from Ayers (1965) (with permission, see credits).

from Mitchell (1961) has been reproduced on the figure to show mean values of the 40° N to 70° N latitude belt in the Northern Hemisphere. It shows a lesser increase than found in the Lake Michigan region. Importantly, Mitchell's curve (Fig. 13) shows a lesser increase and a decline beginning around 1940 for the Northern Hemisphere, whereas the values for the Great Lakes stations show a continuing increase through 1960. Recent period normals appear more appropriate for describing the current temperature climate of the Lake Michigan region than others of longer duration.

The effect of large-city growth on temperatures measured in the city is considerable (Landsberg, 1970). The possible impact of this effect on the long-term temperature trend in the Lake Michigan region is shown in Figure 14 (Ayers, 1965). Data from three large cities (Chicago, Detroit, and Milwaukee) were averaged and compared with averages of two small towns west of Lake Michigan in Illinois. Comparison of these curves reveals that the large-city air temperatures increased at a greater rate, particularly after 1920. Thus, the small-town average curve (Fig. 14) indicates about 0.5°C (0.9°F) increase from 1901 to 1956, whereas the large-city values show an increase of nearly 1°C (1.8°F), suggesting that 0.5°C of this increase is due to urban effects and not to large-scale climatic warming. Thus, part of the 2°C (3.6°F), 110-year increase (Fig. 13) is due to urban effects and not climatic shifts.

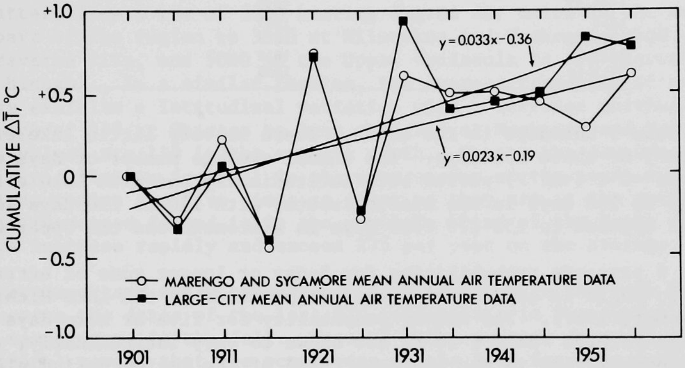


Fig. 14. Trends of Air Temperature at Small-Town (Marengo and Sycamore, IL) and Large-City (Chicago, IL; Detroit, MI; and Milwaukee, WI) Stations in the Great Lakes Basin. Modified from Ayers (1965) (with permission, see credits).

Temperatures in the winter and summer seasons both indicated a gradual temperature increase since 1900 in the region (Ayers, 1965). However, the spring temperatures showed no systematic change, and the fall temperatures showed a slight decrease with time.

Ayers (1965) also identified the extremely cold and warm years during the 1805-1960 period (Table 5). Consideration of their occurrence shows a preponderance of cold years during the first third of the period (1805-1850), with 13 cold years as compared to six in the 1851-1900 period and seven in the 1901-1950 period.

DAILY TEMPERATURES

Extreme daily temperatures can be critical, both in planning of human activities and in the design of industrial activities. Degree day units, another measure of accumulated temperature, are used in estimating seasonal heating and cooling requirements.

The annual average number of days with maximum temperatures above 32°C (90°F) varies latitudinally from 25 days in the south to 15 in the central and

Table 5. Extremely Cold and Warm Years in 1805-1960 Period in the Lake Michigan Region (Ayers, 1965)

Cold Years	*Severest Cold Years*	*Warm Years*	*Severest Warm Years*
1950-51	1950	1953	1931
1935-37	1917	1931	1921
1917	1875	1921	1878
1912	1856	1908-11	1846
1904	1836	1881-82	1811
1893		1877-78	
1885		1870	
1875		1846	
1855-57		1830	
1843		1825	
1835-38		1819	
1831		1811	
1812-18		1808	

with less than 5 hot days in the north. There is very little lake effect on the frequency of these hot days. The annual average number of days with temperatures <0°C (<32°F) varies both latitudinally and with lake effects. The average is 130 days in the extreme south, with 140 to 150 days in lower Michigan as opposed to 150-170 cold days in Wisconsin and the Upper Peninsula.

Table 6 presents probabilities for 5-day or longer runs of extreme temperatures to begin in any week for various portions of the Lake Michigan region (Decker, 1967). The weekly probability for five or more days with maximum temperatures >32°C (>90°F) are shown to vary latitudinally, with the greatest probabilities in the southern third of the region during all summer months. The highest probabilities that runs of cold days [below 0 and -18°C (32 and 0°F)] will occur are in the area west and northwest of Lake Michigan. In most months the probabilities for cold periods in the southwest area are higher than those anywhere east of the Lake. However, the lake effect becomes minimal in February and the probabilities east of the Lake become somewhat higher (at the 0°C level) than those southwest of the Lake.

Table 6. Weekly Probabilities for Runs of Extremes of Temperatures for Points in Various Portions of the Lake Michigan Region

	Percent of the Time					
Weekly Occurrence of 5 or More Consecutive Days	*Southern Third*	*Central Third*	*Northern Third*	*West and North-west of Lake*	*Southwest of Lake*	*East of Lake*
With Maximums >32°C						
June	10	5	2			
July	20	10	5			
August	15	7	3			
With Minimums <18°C						
December				10	5	3
January				20	10	5
February				13	8	8
March				<5	<5	<1
With Minimums <0°C						
Late October				12	3	<1
November				50	35	30
December				75	70	70
January				90	80	80
February				95	80	85
March				75	55	60
April				20	10	20

Heating degree days and cooling degree days are expressions of fuel or power consumption involved in the heating and cooling processes of structures. They are computed on the basis of a temperature of 18°C (65°F), and days in the cold season with mean temperatures that fall below the 18°C level have that difference as the number of heating degree days. For example, if the daily temperature on 1 November is 15°C (59°F), three heating degree days have been accumulated. In a similar fashion, cooling degree days are computed on the basis of warm daily mean temperatures and then accumulated for the entire warm season.

Values of heating degree days in the Lake Michigan region exhibit a latitudinal pattern from a low of 3300 heating degree day units in the extreme southern part of the region to 3850 at Milwaukee and Muskegon, 4400 at Green Bay and Traverse City, and 5000 in the Upper Peninsula (a 50% increase over the value at Chicago). In a similar fashion, the average frequency of cooling degree days exhibits a latitudinal variation with a decrease northward from a regional high of 550 at Chicago to less than 275 at Muskegon and Manitowoc. The lowest values are 110 in the extreme north. Hence, the demands for cooling (based only on climatic factors) in the warm season at the south end of the Lake Michigan region are five times as great as they are at the north end, and most of the increased demand is in the southern third of the Basin where cooling degree days increase rapidly and exceed 275 per year on the average.

Another important daily temperature consideration in the Lake Michigan region concerns the dates of the last 0°C temperature in the spring and the first 0°C temperature in the fall. Maps of these average dates (U. S. Dep. Commer., 1966b) reveal that the occurrence of the last freezing temperature in spring is related to latitudinal, lake, and topographic effects in the Lake Michigan region. In the high country of the Upper Peninsula and of the northern portion of the Lower Peninsula, the average last date is 1 June. In the southern extremes of the region, the last freezing temperature normally occurs on 1 May, and 15 May is the average date through the central portion of the region. In the high country in both peninsulas of Michigan, 15 September is the average first date of freezing temperature in fall, but throughout most of the Lake Michigan region the first freezing date comes normally on 1 October. This is delayed to 15 October along the edges of the southern portion of Lake Michigan as the warm lake waters moderate the air. This is one of the key factors in the development of the fruit belt in the Lower Peninsula of Michigan.

The first and last dates of freezing temperature determine the length of the freeze-free period, often considered to be the growing season. The growing season varies considerably; there are over 170 days in the extreme southwestern portion of the region and over 160 days along and halfway up both sides of the Lake. The season is less than 120 days in the high country of the Upper and Lower Peninsulas and is less than 150 days through much of Wisconsin and lower Michigan. The lake effects do increase the growing season approximately 15 days in the Lower Peninsula, but the effects of the higher elevations are more critical in determining the length of the season, particularly in the northern peninsula.

DIURNAL TEMPERATURE DISTRIBUTION

The diurnal distributions of temperature are much the same throughout the Lake Michigan region. Minimum temperatures typically occur between 0600 and

0700 LST* during the colder half of the year, but are earlier in the warmer half of the year, normally between 0400 and 0600. Seasonal differences also exist in the average time of occurrence of the maximum daily temperatures. Throughout the region, they typically occur between 1300 and 1400 in the cold season and between 1400 and 1600 in the summer season. The typical diurnal cycle occurs on practically all summer days with moderation due only to overcast conditions downwind of the Lake or to temporary reductions in temperature when showers and storms occur. In the winter season the diurnal distribution is not as noticeable, as indicated in Figure 12. There are periods of major cyclonic passages in the winter season which bring long, 24-to-48 hr gradual decreases in temperatures such that the daily maximum temperature may be reached at midnight and the minimum at the following midnight. Another characteristic of winter temperatures, particularly during periods of deep cyclonic storms with overcast rain conditions, is a very flat temperature distribution with the maximum and minimum temperatures differing by only 1 to 3°C (1.8 to 5.4°F). Although the range between maximum and minimum temperatures is greatest in summer in the Lake Michigan region (Fig. 12), in winter the major outbreaks of cold Arctic air bring greater day-to-day temperature changes. Occasional events produce drops in temperatures from 5 to 20°C (9.0 to 36°F) in a period of 12 hours or less. Carlson and Baker (1975--unpublished), in a study of temperatures in the lee of Lake Michigan, also found that there were nocturnal temperature increases of 2 to 10°C (3.6 to 18°F) during 2-3 hour intervals during the middle of the night in the area within 20-30 km (12-19 mi) of Lake Michigan. These occur on approximately 30% of all nights, and appear to be related to lake-induced processes.

MOISTURE

PRECIPITATION

Precipitation is the primary source of fresh water in the Lake Michigan region. The water used for domestic purposes, agriculture, navigation, industry, and recreation depends upon the amount and the variability of precipitation. This section presents a variety of precipitation statistics related to understanding the phenomena and to using the information in design and planning.

Precipitation is measured using two types of raingages. The most commonly used is a non-recording type which has a 20 cm (8 in.) orifice located 78 cm (31 in.) above ground. Measurements are made once daily using a ruler inserted into a cylinder inside the raingage. The amount of snowfall is measured by averaging ruler samples taken in the snow around the raingage. The recording raingages are not as common, representing 50 of the 300 gages in the Lake Michigan region. A typical gage catches precipitation in a bucket and weighs it; the amount and time are recorded on a clock-driven chart. These charts are changed daily or after each rain; daily and hourly values are determined.

Annual and Seasonal Values

The average annual precipitation pattern for the Lake Michigan region is presented in Fig. 15, and is based on data for 1931-1965. The lowest values,

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All times are local standard time (LST) unless specified. Time is expressed as 24-hr time (instead of standard 12-hr time) in this report. An example of 24-hr time is shown in Figure 57.

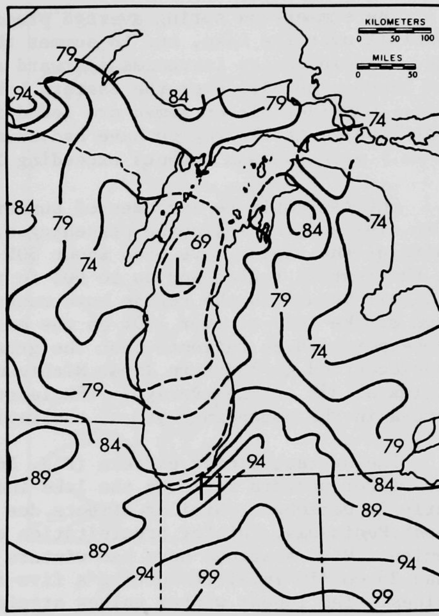


Fig. 15.

Average Annual Precipitation, cm. Modified from Changnon (1968b).

<68 cm (<27 in.), occur over the Lake whereas the highest values, up to 94 cm (37 in.), occur southeast of the Lake. In general, values increase in all directions away from the Lake. Average annual precipitation over the Lake is 1-6% less than that over the Basin (Changnon, 1968b). Lake effects result in increases of 1-20% in annual precipitation over most portions of upper and lower Michigan.

Annual precipitation values at any given point vary considerably between years. All weather stations in the region have experienced over 100 cm (39 in.) per year, and many have recorded totals over 130 cm (51 in.). Precipitation in any year can also vary considerably within the region, although when extremely low annual precipitation occurs, low values typically extend over most of the region. The lowest values recorded throughout the region are usually less than 50 cm (20 in.) with extremes of less than 40 cm (16 in.) at some stations. The Basin's annual precipitation has declined 5 to 8 cm (2 to 3 in.) since 1863 and it has a 75-year oscillation with an amplitude of 8 cm (3 in.) (Muller *et al.*, 1965).

An estimate of the lowest expected precipitation at any given locale can be made in the following manner. In the extreme southern end of the region, the lowest annual values will be 70% of the annual averages shown in Figure 15. These low percentages decrease to 60% of the annual averages in the central section and are 55% in the extreme north. In a similar fashion, the maximum likely annual precipitation values can be estimated. Annual maxima in the north are 130 to 140% of the averages (Fig. 15), whereas they become 160% of the average in the south. Comparison of these percentage departures from the average annual rainfall reveals that departures are typically ±40% in the north, but in the south range from 40% below to 60% above, reflecting skewness towards very heavy annual totals.

The summer and spring average precipitation patterns (Fig. 16) show low rainfall over the Lake, and in summer the low extends inland into lower Michigan. Precipitation increases eastward across Lake Michigan in fall and winter and becomes heavier over the eastern Lake and lower Michigan than on the west side. Considerable extremes are found in the seasonal precipitation values. Most locales in the region have had summer season rainfalls of under 15 cm (6 in.) with maximum amounts exceeding 50 cm (20 in.).

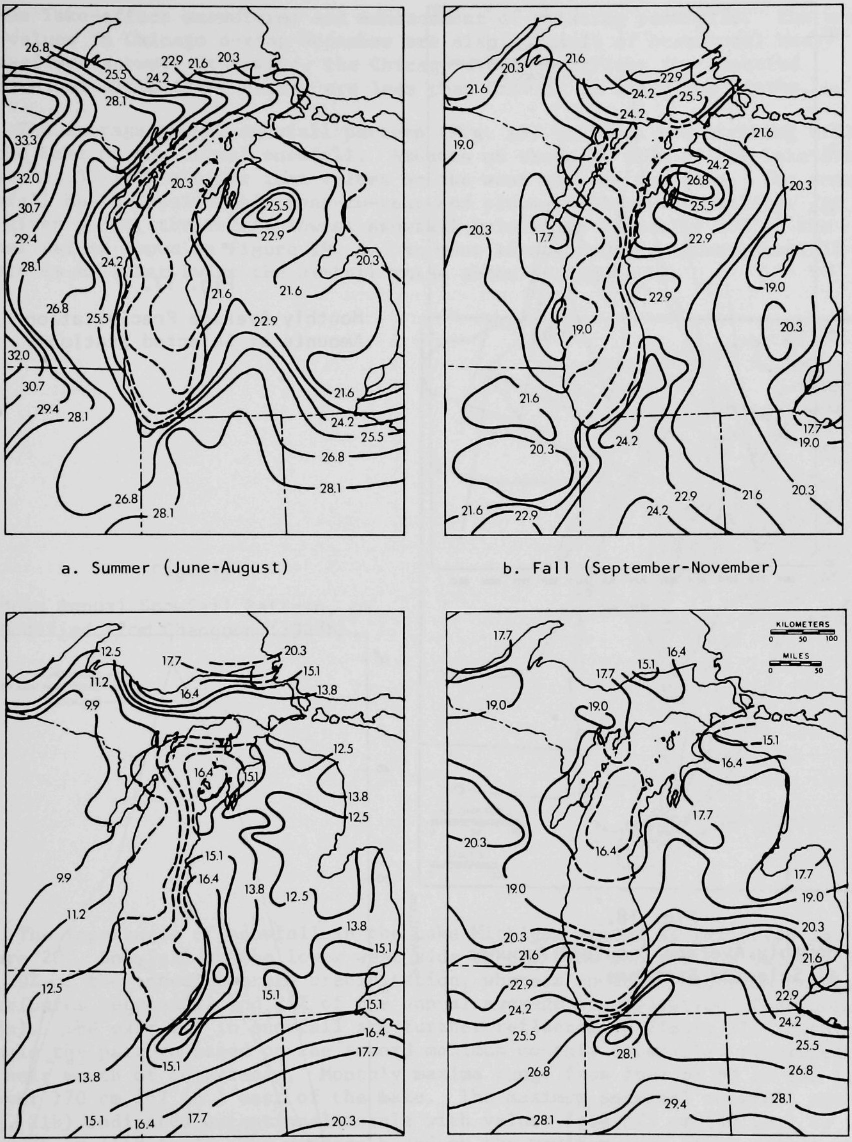
One can estimate extremes of summer precipitation using the mean pattern (Fig. 16) and the following percentages. Record low values in the southern third of the region have been about 30% of average values; they increase to 40% in the central region and up to 60% in the north. The record high summer rainfall values in the region have ranged from 190% of the average on the west side of the Lake to over 220% on the east side of the Lake. Integration of these percentages reflects that the greatest extremes of summer precipitation have occurred in southern lower Michigan with the maxima over 220% and the minima at 35% of the average. The least variability of the summer rainfall occurs in the northern third of the region.

The average winter pattern (Fig. 16) is totally unlike that of the summer. The winter pattern reflects the lake-induced enhancement of snowfall, particularly in December. Similar effects due to Lake Superior can be noted in the Upper Peninsula. Winter precipitation extremes have been considerable in the region. Most stations have had winters with less than 5 cm (2 in.) and more than 25 cm (10 in.), reflecting a five-fold range between the lowest and highest values. The lowest winter values attained throughout the region have been between 30% and 40% of the averages shown in Figure 16. However, the highest winter values show a west-to-east decline. Maximum winter totals west of Lake Michigan have exceeded 200% of the average values, whereas those on the east side of the Lake have ranged from 160-170% of their averages.

The average precipitation pattern in spring (Fig. 16) shows the least influence of the Lake. The spring pattern generally has a latitudinal orientation of isohyets; however, the fall pattern shows the sizeable influence of the Lake on precipitation. This indicates an increase of up to 30% of that expected without the Lake in portions of lower Michigan.

Monthly average precipitation amounts for three selected stations representing the extreme south (Chicago), east central lake-effect area (Muskegon), and the northern portion of the region (Crivitz) appear in Figure 17. February is the driest month of the year at all locales. Inasmuch as precipitation tends to have a latitudinal decrease from south to north, except during midsummer in the Midwest, the Chicago values should be the highest in most months. However, higher values occur at Muskegon during September through February, which reveals that the Lake enhances fall convective storms and winter lake snowfalls. Conversely, from April through August, the values at Muskegon are less than expected and lower than Crivitz, Wisconsin. Once again this is due to lake effects which reduce convective activity. Hence, the maximum rainfall month for Muskegon and other eastern portions of the region under lake influence is September, as compared to June, the month of maximum precipitation in the western half of the Lake Michigan region.

The average monthly snowfall values for the same three stations appear in Figure 18. The sizeable values at Muskegon in most months reveal the magnitude



a. Summer (June-August)

b. Fall (September-November)

c. Winter (December-February)

d. Spring (March-May)

Fig. 16. Average Precipitation Patterns, cm. Modified from Changnon (1968b).

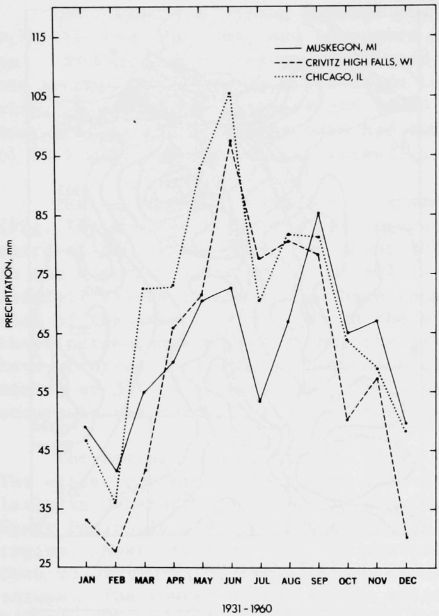


Fig. 17.
Monthly Average Precipitation Amounts at Selected Stations.

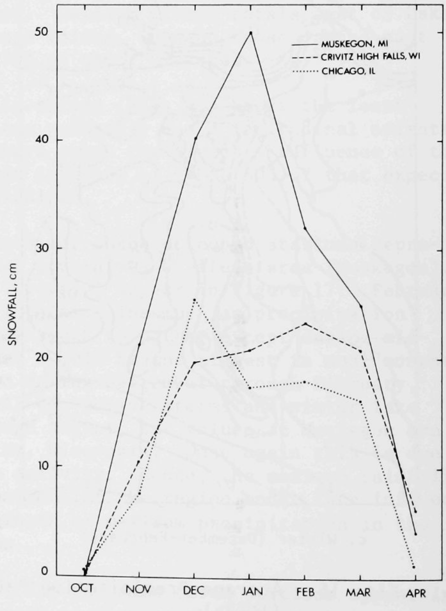


Fig. 18.
Monthly Average Snowfall Amounts at Selected Stations.

of the lake-effect snowstorms and enhancement of existing snowfalls. The maximum values in Chicago during December are also a result of occasional heavy lake-effect snows. Otherwise, the Chicago averages reflect the expected latitudinal difference; values are less than Crivitz in all other months.

The average annual snowfall pattern (Fig. 19) reflects the striking effect of the Lake on the annual snowfall. Amounts on the east side of the Lake are typically 50-100% greater than values on the west side of the Lake. The annual snowfall has a considerable year-to-year and place-to-place variability. At any given point, the record lowest snowfall values are typically 30% of the annual values shown in Figure 19, and at most locations the highest snowfall on record is at least twice the average value shown in Figure 19.

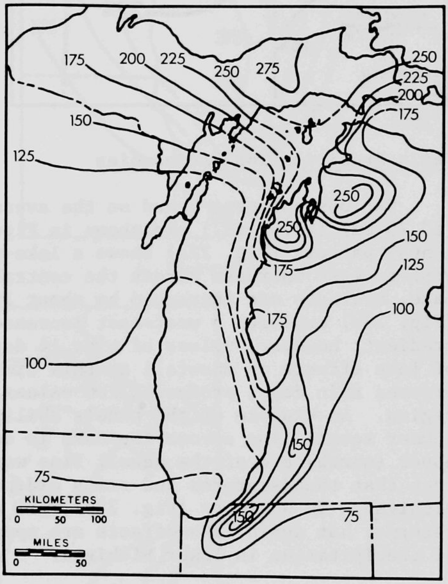


Fig. 19.
Mean Annual Snowfall Pattern, cm.
Modified from Changnon (1968b).

The importance of snowfall in the Lake Michigan region is reflected in Figure 20. Snowfall on the lower west side of the Lake contributes between 16 and 20% of the annual average precipitation, whereas in lower Michigan snowfall contributes between 22 and 26% of the annual average precipitation (Changnon, 1968b). The extremes in snowfall are further reflected in Figure 21. Figure 21a reveals the pattern based on the record maximum monthly snowfalls, regardless of their month of occurrence. Monthly maxima range from lows of 80 cm (31 in.) to over 170 cm (67 in.) east of the Lake. The maximum seasonal snowfall pattern (Fig. 21b) indicates exceptional totals with values from 175 cm (69 in.) to over 375 cm (148 in.). The pattern based on the maximum snow depth values ever recorded (Fig. 21c) indicates a range from 65 cm (26 in.) in the south to over 95 cm (37 in.) in the north. The maximum snow depth values generally reflect latitudinal controls, whereas the record monthly and seasonal patterns reflect the lake effect (Ludlum, 1962).

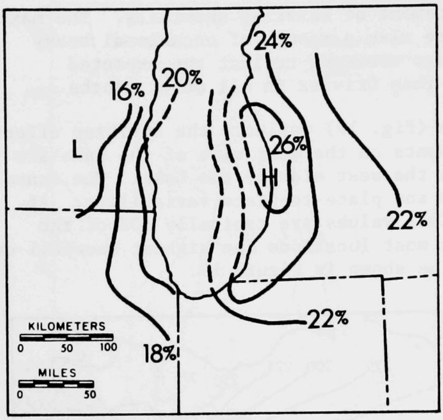


Fig. 20.

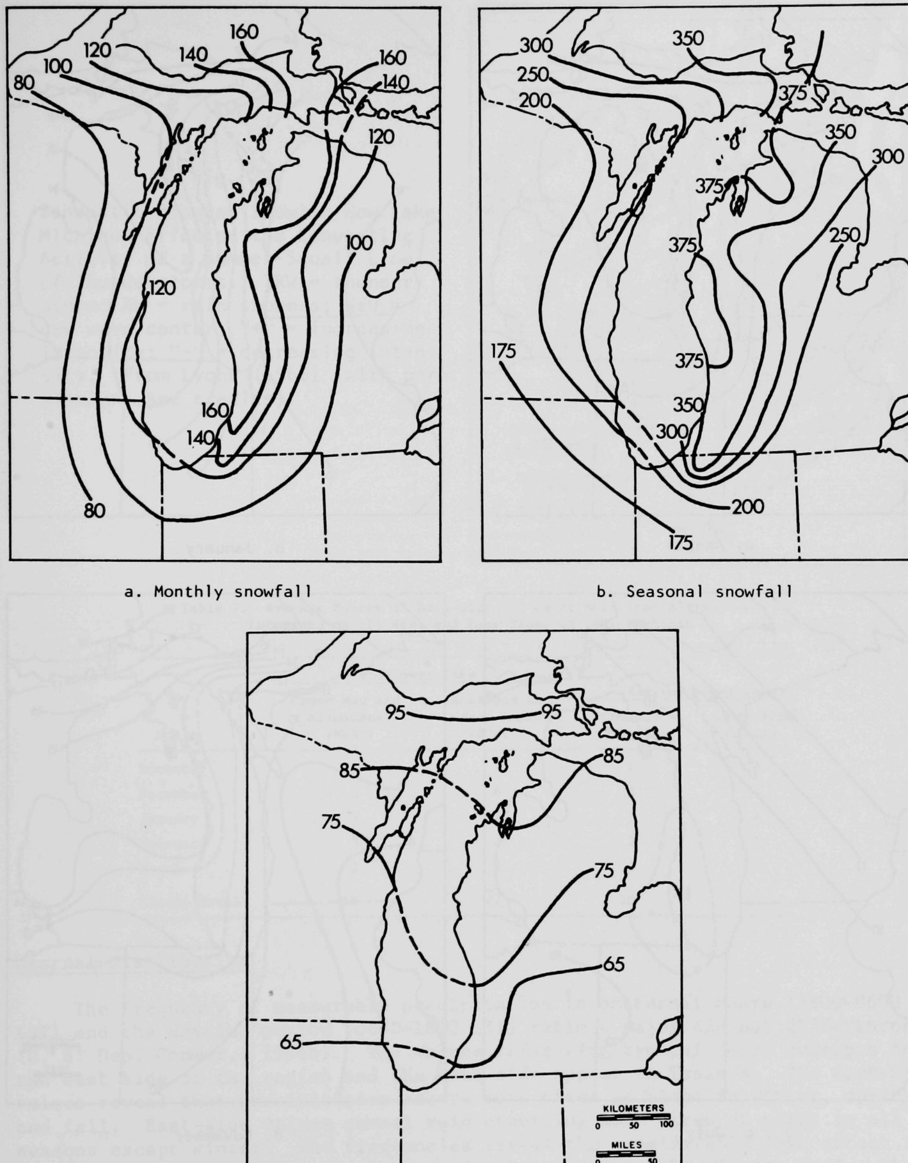
Percent of Total Average Annual Precipitation Occurring on Days with Measurable Snowfall. Redrawn from Changnon (1968c) (with permission, see credits).

Daily Precipitation Frequencies

Various patterns based on the average number of days of measurable rain (≥0.25 mm) (≥0.01 in.) are shown in Figure 22 (U. S. Dep. Commer., 1966b). The annual pattern (Fig. 22a) shows a lake-produced distortion from the general west-to-east increase across the central United States. In the lee of the Lake, averages are increased by about 10 days. The average pattern for January (Fig. 22b) exhibits a west-east increase which is a part of the general climatic gradient; however, values of over 14 days occur in lower Michigan as a result of lake effects on snowfall at this time. In July (Fig. 22c) the Lake suppresses rain days, producing low values over the southeastern portion of the region. An example of the Lake's ability to retard motion of a well-developed summer squall line across the Lake is depicted in Figure 23 (Lyons, 1966). The upper (north) end of the squall line was bent and the length then decreased such that thunderstorms and rains did not cross the Lake and occur in lower Michigan. In November (Fig. 22d), the west-to-east gradient of rain days returns, but again lake effects are apparent and produce an additional two days of precipitation in lower Michigan.

The regional distribution of days with heavy snowfall, >2.5 cm (>1 in.), is similar to that of the measurable rain days (Fig. 22). The considerable effect of the Lake on heavy snowfall frequencies is revealed in Table 7. West-to-east increases exist at both the lower- and the middle-lake areas. The seasonal totals in the lee of the Lake are nearly twice those upwind. Record daily snowfalls at all points have been more than 40 cm (16 in.), and at locations south of the Upper Peninsula totals have exceeded 60 cm (24 in.). In the Upper Peninsula, record daily snowfalls have exceeded 70 cm (28 in.).

The region also experiences occasional ice (glaze) storms produced by freezing rains. In the south, the average number of these storms at a point is 12 to 15 per year, but the frequency decreases northward to less than five days per 10 years in the extreme north. Ice thickness in the south has been measured to 2 cm (0.8 in.) on communication wires (Changnon, 1969).

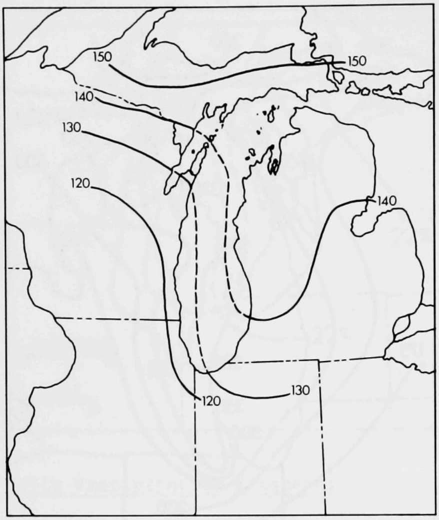


a. Monthly snowfall

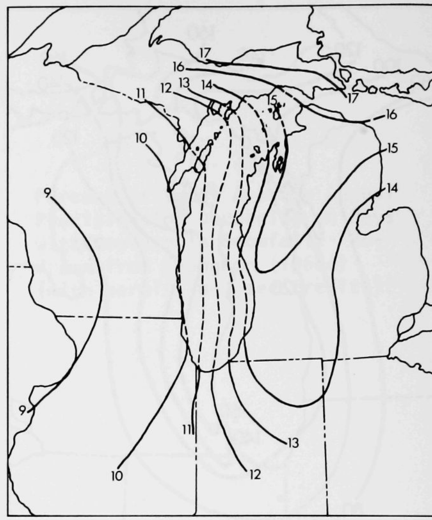
b. Seasonal snowfall

c. Snowdepth

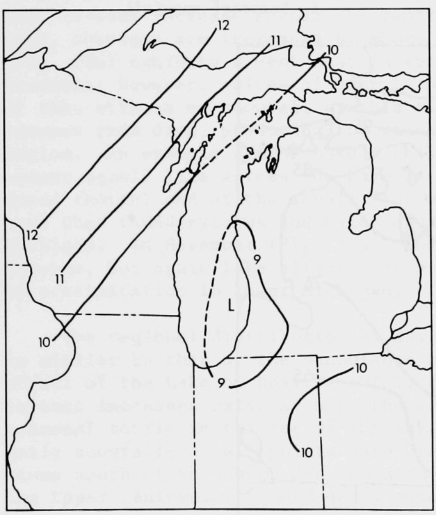
Fig. 21. Record Maximum Extremes of Snowfall, cm.



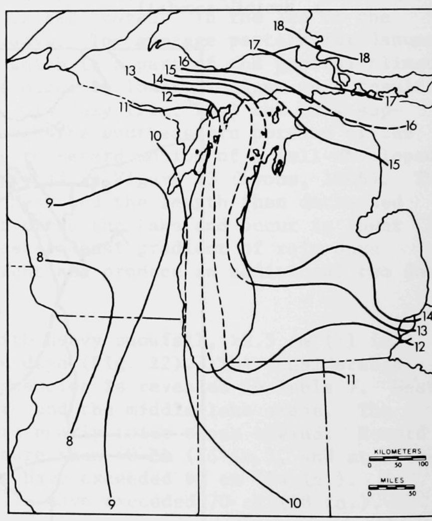
a. Annual



b. January



c. July



d. November

Fig. 22. Average Frequency of Days with Measurable (≥0.25 mm) Precipitation.

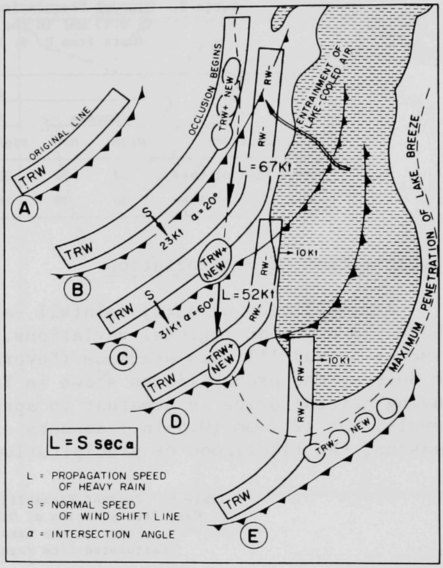


Fig. 23.

Schematic Diagram Showing How Lake Michigan Affected the Convective Activity of a Summer Squall Line of Thunderstorms. TRW = thunderstorm; RW = rain showers; NEW = new wave center; "+" = increasing intensity; "-" = decreasing intensity. From Lyons (1966) (with permission, see credits).

Table 7. Average Number of Days with 2.5 cm or More Snowfall at Two Locations on the West and East Sides of Lake Michigan

	Mid-Lower Lake		*Extreme Lower Lake*	
Month	*Green Bay and Milwaukee (West)*	*Muskegon and Grand Rapids (East)*	*Chicago (West)*	*South Bend (East)*
November	1	3	1	3
December	3	6	3	4
January	3	6	2	4
February	3	4	2	4
March	2	3	2	2
Season Total	12	22	10	17

Diurnal Distribution

The frequency of measurable precipitation in nocturnal hours (1800-0600 LST) and the daytime period (0600-1800 LST) reflect major diurnal differences (U. S. Dep. Commer., 1966b). The values reflecting typical point averages for the west side of the region and the east side appear in Table 8. The west-side values reveal that precipitation occurs more often at night in winter, spring, and fall. East-side values reveal rain occurring more often at night in all seasons except winter. The frequencies reveal the considerable lake effect in the winter, summer, and fall, but not in the spring. Lake effects during the summer reduce frequency of precipitation both in the night and day periods; in the fall and winter there are sizeable increases in the night and day occurrences of precipitation on the east side of the Lake.

Table 8. Diurnal Frequencies of Measurable Precipitation
($\geq$ 0.25 mm) in the Lake Michigan Region
(Data from U. S. Dep. Commer., 1966b)

	Percent of the Time							
	January		April		July		October	
Location	Night	Day	Night	Day	Night	Day	Night	Day
West side of Lake	22	20	28	25	20	20	18	16
East side of Lake	36	38	28	26	17	15	23	19

Probabilities of Precipitation

Probabilities of daily rainfall vary seasonally within the region but there are no great regional variations. The point values from Michigan, Wisconsin, and Illinois stations (Feyerherm *et al.*, 1966) have been summarized to develop the probabilities shown in Table 9. The likelihood of a given day having precipitation is greatest in spring for the two lower precipitation levels, but 12.7-mm (0.5-in.) amounts are more likely in summer. In all seasons, the likelihood of precipitation is least in winter.

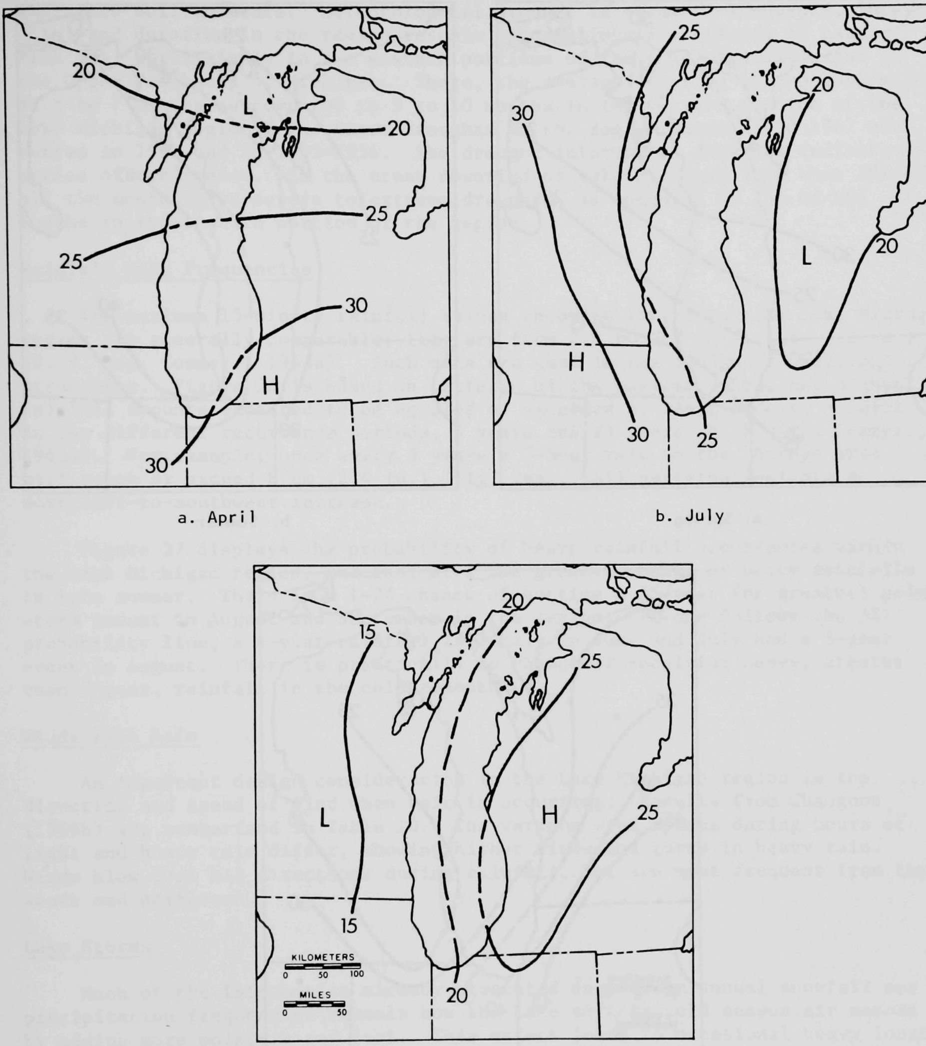
Table 9. Percent Probability That Any Given Day Will
Have Precipitation of Different Amounts at Any
Point in the Lake Michigan Region
(Calculated from Feyerherm *et al.*, 1966)

Season	$\geq$0.25 mm	$\geq$5 mm	$\geq$12.7 mm
Spring	34	17	8
Summer	30	15	10
Fall	25	12	6
Winter	24	8	3

Probabilities for heavy weekly precipitation and for short-term, 3-week, dry periods are also relevant to various activities in the Lake Michigan region. Probabilities of weekly precipitation $\geq$2.5 cm ($\geq$1 in.) (Barger *et al.*, 1959) at a point for any week during April, July, and October appear in Figure 24. The April pattern shows latitudinal distribution with greater probability of rainfall in the south. In July, there is a west-east decrease in probabilities, partially resulting from the detrimental lake effects on convective activity. The converse is apparent in October when lake effects make point probabilities greater than 25% for a 2.5-cm (1-in.) weekly rainfall as opposed to only 15% chance west of the Lake.

The chance of receiving less than 2.5 cm precipitation (at a location) in any 3-week period during spring (Fig. 25a) is much higher in the north. Lake effects in summer decrease convective activity and produce a sizeable increase in the chance for dry 3-week periods in lower Michigan. Lake effects in fall reverse this tendency with a sharp decrease in probabilities across the lower portion of Lake Michigan.

The frequency of meteorological droughts (Strommen *et al.*, 1969) is not excessive in the Lake Michigan region. Meteorological drought is calculated on the basis of precipitation, evapotranspiration, and runoff to reflect the

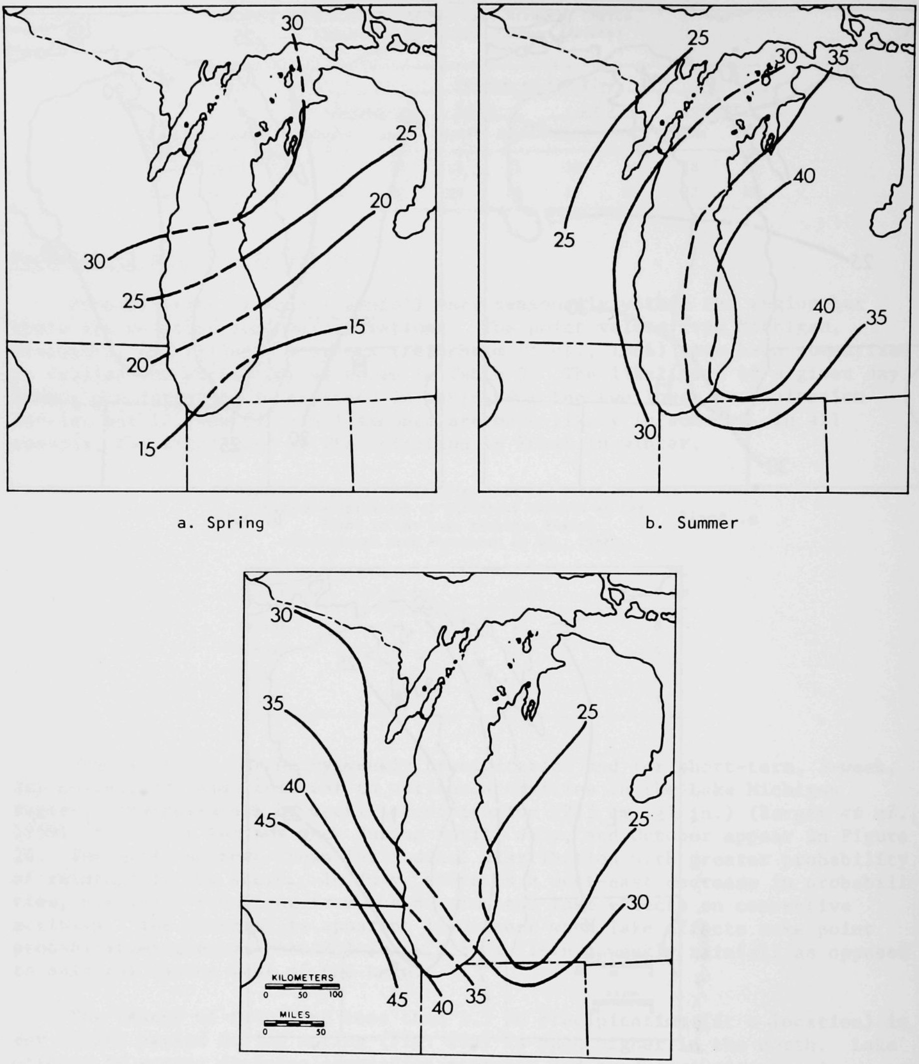


a. April

b. July

c. October

Fig. 24. Percent Chance of ≥2.5 cm Precipitation in Any Week in a Given Month.



a. Spring

b. Summer

c. Fall

Fig. 25. Percent Chance of <2.5 cm Precipitation in Any 3-Week Period in a Given Season.

available soil moisture. Meteorological drought in terms of frequency, intensity, and duration in the region reveals the ameliorative effects of Lake Michigan, particularly in the western portions of the Lower Peninsula and in the Upper Peninsula of Michigan. There, the average duration of drought periods is 6 to 7 months as compared to 9 to 10 months in the western portion of the Lake Michigan region. The worst droughts in the region during 1930-1967 occurred in 1931 and in 1953-1956. The drought information does not indicate any cycles of occurrence. In the areas downwind of Lake Michigan less than 10% of all the months have severe to extreme droughts, as compared to 15% of the months in the western portion of the region.

Rainfall Rate Frequencies

The maximum 15-minute rainfall values recorded throughout the Lake Michigan region are generally comparable; they are from 2.8 to 3.3 cm (1.1 to 1.3 in.) (U. S. Dep. Commer., 1963a). Such data are used in the design of hydrologic structures. Figure 26 is based on patterns of the maximum 3-hour and 24-hour rainfall amounts expected to be equaled or exceeded at least once at a point in two different recurrence periods, 5 years and 25 years (U. S. Dep. Commer., 1963a). For example, once every 5 years a 3-hour rain in the Chicago area will reach or exceed 6 cm (2.4 in.) (Fig. 26a). All patterns indicate a northeast-to-southwest increase.

Figure 27 displays the probability of heavy rainfall occurrences within the Lake Michigan region, and indicates the greater chance of heavy rainfalls in late summer. There is a 1-2% chance of getting a 25-year (or greater) point storm amount in August and September in the region. If one follows the 5% probability line, a 4-year rainfall is likely in June and July and a 5-year event in August. There is practically no chance of receiving heavy, greater than 2-year, rainfall in the colder months.

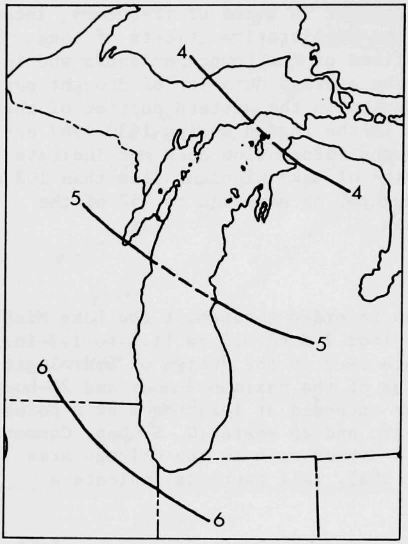
Winds with Rain

An important design consideration in the Lake Michigan region is the direction and speed of wind when rain is occurring. Results from Changnon (1966b) are summarized in Table 10. The various wind speeds during hours of light and heavy rain differ, showing higher winds and gusts in heavy rain. Winds blow from all directions during rainfall, but are most frequent from the south and northeast.

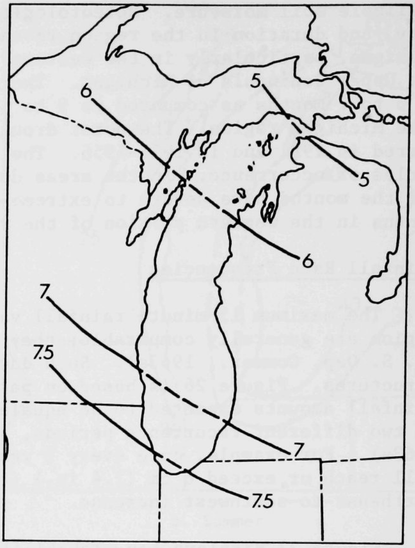
Lake Storms

Much of the information already presented on average annual snowfall and precipitation frequencies reveals how the Lake affects cold season air masses by adding more moisture and heat. This effect leads to occasional heavy local snowstorms that deposit snow parallel to the Lake.

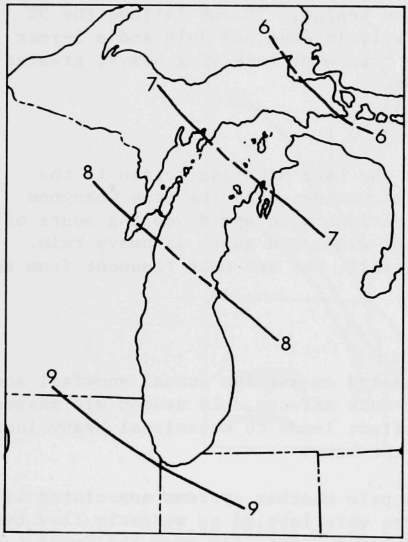
Eichenlaub (1964) identified the synoptic weather systems associated with the occurrence of lake-effect snows. These were labeled as westerly flow types, usually consisting of a strong westerly flow of arctic air over the Great Lakes with a low pressure center somewhere to the east. The gradient wind direction and the speed and length of air trajectory (fetch) across Lake Michigan are controlled by the position of the low. On the average, the lake water is



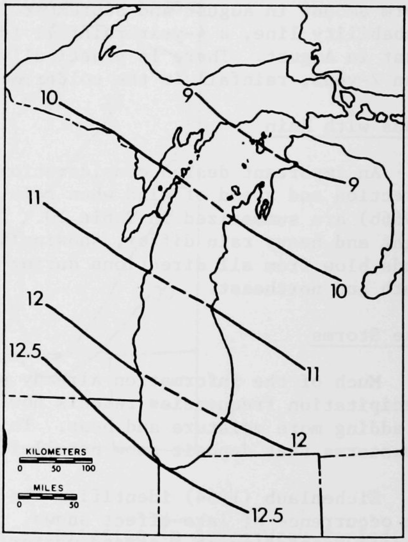
a. 3-hr amounts in 5 yr



b. 3-hr amounts in 25 yr



c. 24-hr amounts in 5 yr



d. 24-hr amounts in 25 yr

Fig. 26. Patterns of Heavy Rainfall Point Values, cm, for 3- and 24-hr Durations Expected to Occur at least Once in 5- and 25-yr Periods.

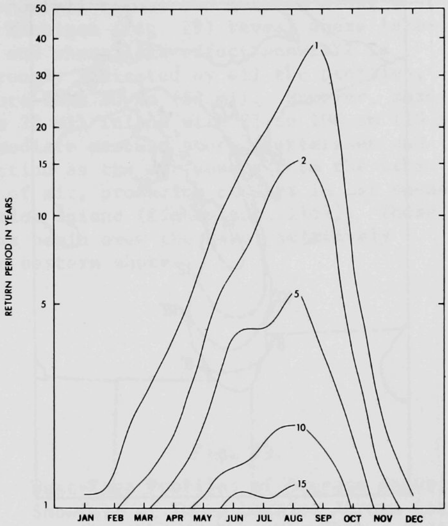


Fig. 27.

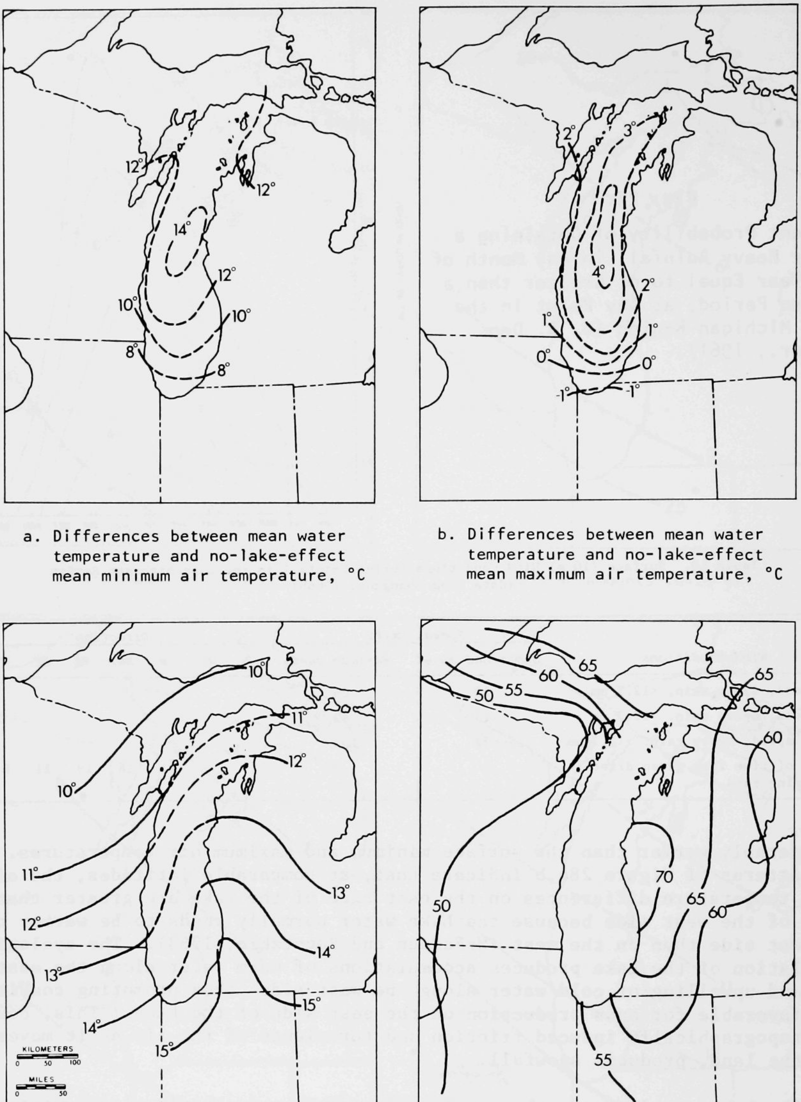
Percent Probability of Obtaining a 24-hr Heavy Rainfall in Any Month of Any Year Equal to or Greater than a Return Period, at Any Point in the Lake Michigan Region (U. S. Dep. Commer., 1961).

Table 10. Surface (10 m) Wind Conditions During Rainfall in the Lake Michigan Region (Data from Changnon, 1966b)

	Speed, km/hr		*Direction*							
Wind Conditions	*Sustained speed*	*Maximum gusts*	*N*	*NW*	*W*	*SW*	*S*	*SE*	*E*	*NE*
Mean speed, light rain, <12.7 mm	10	26								
Mean speed, heavy rain, >12.7 mm	15	42								
Highest speed, heavy rain, >12.7 mm	32	105								
Percent of time from given direction during rain			11	6	11	16	19	11	8	18

considerably warmer than the surface minimum and maximum air temperatures. The patterns of Figure 28a,b indicate that, at comparable latitudes, the air-water temperature differences on the east side of the Lake are greater than those of the west side because the Lake water normally tends to be warmer on the east side than on the west (McFadden and Ragotzkie, 1963). The cyclonic circulation of the Lake produces accumulations of warm water along the east side and upwelling of cold water along the west side, thus promoting conditions more favorable for snow production on the east side of the Lake. This, coupled with topographically induced friction and turbulence of the air as it moves over the land, produces snowfall.

The Lake can increase the atmospheric moisture in the low-level winter air mass (Fig. 28c). The dewpoint temperatures at noon on the lee side of the Lake are 1 to 3°C (1.8 to 5.4°F) higher than those on the upwind side. The lake effect on the winter lapse rate is also shown by the average cloudy-sky pattern (Fig. 28d); cloudy days are 40% more frequent in western lower Michigan than in eastern Wisconsin.



a. Differences between mean water temperature and no-lake-effect mean minimum air temperature, °C

b. Differences between mean water temperature and no-lake-effect mean maximum air temperature, °C

c. Mean dew point temperature, °C, 1230-1300 CST

d. Mean number of cloudy days

Fig. 28. Patterns of Winter Weather Conditions. Modified from Changnon (1968b).

Profiles based on average annual snowfall values and located along west-east lines from Wisconsin across lower Michigan (Fig. 29) reveal where lake-effect snowfalls develop over the Lake and where lake-effect snowfall is maximized. Lake-effect snowfall is strongly indicated by all the profiles, and it extends inland from the shore more than 80 km (50 mi). However, maximization occurs from 20 to 40 km (12 to 25 mi) inland with 25 to 100 cm (10 to 39 in.) more snow there than at the immediate eastern shore (Petterssen and Calabrese, 1959). Added low-level friction as the air passes from the Lake onto the land surface causes a pile-up of air, producing changes in air speed and direction that enhance snow production inland (Eichenlaub, 1964). These findings indicate that lake-effect snows begin over the Lake, relatively close, 10 to 30 km (6 to 19 mi), to the eastern shore.

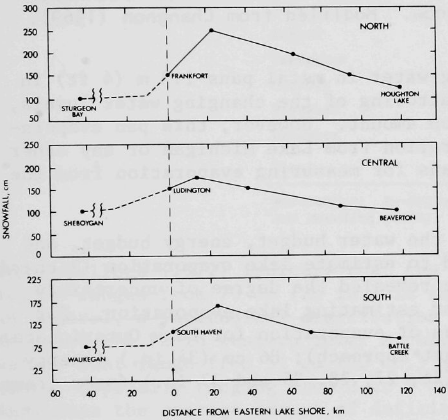


Fig. 29.

West-East Profiles of Average Annual Snowfall at Three Locales Across Lake Michigan and Western Michigan. Modified from Changnon (1968b).

Lake Michigan also occasionally causes or intensifies severe winter storms along the western shore of the Lake (Williams, 1963). In these instances, a migratory cyclone passes south and east of the region producing low-level winds from the east through northwest. The more northerly winds have a long fetch across Lake Michigan towards the lower west side. Changnon (1969) found that 31 to 410 severe winter storms in Illinois during 1900-1960 had snowfall maximums in close proximity to Lake Michigan that were a direct result of lake effects. Most of these storms occurred in November and December when the Lake was relatively warm. Differences in the placement of the maximum snowfall (Fig. 30) are due to the course of the migratory cyclones and hence in the direction of the most persistent flow across Lake Michigan.

EVAPORATIVE PROCESSES

Evaporation and evapotranspiration are major factors in the climate of the Lake Michigan region. The amount of moisture returned to the atmosphere over the land area is more than half of the annual precipitation. Evaporation from Lake Michigan has been estimated to be 10 cm (4 in.) greater than the amount of precipitation [74 cm (29 in.) for average lake precipitation versus 84 cm (33 in.) for evaporation] (Jones and Meredith, 1972). However, values of evaporation and evapotranspiration from lake and land surfaces are not well established.

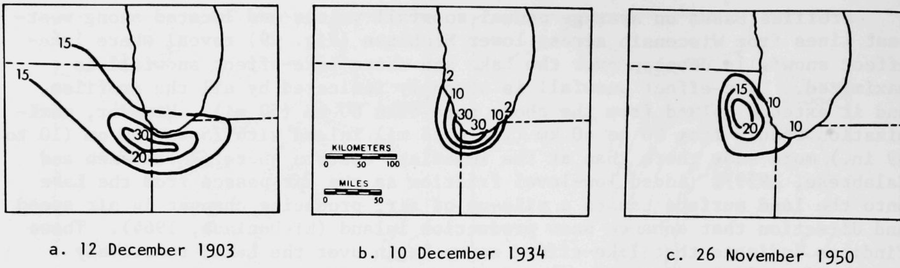


Fig. 30. Examples of Lake-Induced Severe Winter Storms on the Southwest Side of Lake Michigan, cm snow. Modified from Changnon (1969).

Evaporation has been measured using water in metal pans 1.3 m (4 ft) in diameter and 0.3 m (1 ft) in depth. Monitoring of the changing water levels, done once daily, provides the evaporation amount. However, this pan evaporation is not representative of the evaporation from Lake Michigan or any other lake. Actually, there are no direct means for measuring evaporation from the surface of a lake.

Various empirical means, including the water budget, energy budget, and mass transfer methods, have been applied to estimate lake evaporation (Richards, 1969). Richards and Rodgers (1964) have revealed the degree of uncertainty reflected in these varying approaches for estimating lake evaporation. For example, the various scientific estimates of evaporation for Lake Ontario are: 63 and 79 cm (25 and 31 in.) (water budget approach); 86 cm (34 in.) (energy budget); and 66, 68, 71, 90, and 94 cm (26, 27, 28, 35 and 37 in.) (mass transfer approach).

Two sets of estimates (A and B) of the average annual evaporation from Lake Michigan are presented in Table 11, and these reveal the considerable differences that can be obtained through slightly different approaches. The difference in the totals, 24.8 cm (10 in.), is 41% more than the lower estimate, A. The greatest differences are in the fall and early winter.

Jones and Meredith (1972) also estimated the individual monthly and annual evaporation from Lake Michigan for the 1946-1965 period. Their annual evaporation values varied widely, ranging from a low of 66 cm (26 in.) in 1951 to a high of 97 cm (38 in.) in 1958. Several months in addition to June and July exhibited negative evaporation values, particularly April and May. Their approach (see B in Table 11) indicates that September has the maximum evaporation of 15.4 cm (6 in.); individual values for September over the 20-yr period range from a low of 6 cm (2.4 in.) in one year to a high of 25 cm (10 in.) in another year. Hence, the amount of evaporation over Lake Michigan has considerable year-to-year variability.

Evapotranspiration, the movement of moisture to the atmosphere from the land and plants, is a function of the energy available for the evaporation of water from soil and plants. Like lake evaporation, it also is not directly measured, but estimations have been made of the actual evapotranspiration (AE) and the potential evapotranspiration (PE). The PE is that amount of evapotranspiration that would occur if the soils were always saturated. Phillips

Table 11. Monthly Evaporation Values from Lake Michigan, Estimated Using Mass Transfer Approaches

Month	*Estimate, cm* A	B
January	7.6	8.6
February	6.6	6.4
March	4.3	5.1
April	1.0	2.0
May	-2.0	1.8
June	-3.0	-0.5
July	3.0	-0.1
August	7.9	9.3
September	10.0	15.4
October	8.6	10.4
November	7.1	13.6
December	7.6	11.6
Total	58.8	83.6

References: A--Snyder (1960); B--Jones and Meredith (1972).

and McCulloch (1972) indicate that the average annual PE in the Lake Michigan region ranges from 70 cm (28 in.) in the south to 55 cm (22 in.) in the north. In general, a latitudinal distribution is shown although lake effects do increase the PE in western lower Michigan. Calculations of AE result in values that range from 51 cm (20 in.) in the north to 67 cm (26 in.) in the south, typically ranging from 3 to 5 cm (1.2 to 2.0 in.) below the PE. This indicates the average amount of deficit in the soil moisture in the region. Little topographic effect is seen in the patterns of AE and PE in the Lake Michigan region, but lake effects are evident and lead to decreased AE and PE along both lakeshores. Average AE rates in winter on the eastern shore are from 13% greater in the south to more than 60% greater in the north than expected from latitudinal predictions (Changnon and Jones, 1972). In the summer months, when evapotranspiration is greatest, the Lake does not affect it.

ATMOSPHERIC MOISTURE

The amount of moisture in the air is critical for determining the amount of evaporation from water and the amount of evapotranspiration from plants and soil. The amount of atmospheric moisture also helps determine the occurrence of fog, clouds, and precipitation. Relative humidity (the amount of moisture in the air expressed as a percent of the amount it can hold at a given temperature) and the dewpoint temperature (the temperature at which the moisture in the air will condense) are common measures of atmospheric moisture. These are measured by hygrometers and other devices which have moisture-sensitive elements (*e.g.* blond human hair) that expand or contract with changing moisture and indicate the relative humidity.

Table 12 summarizes the average relative humidity values during the day at four stations throughout the Lake Michigan region. January mid-day relative

Table 12. Diurnal Distributions of Relative Humidity (%) in the Lake Michigan Region

Location	Month	Time 0100	0700	1300	1900
Escanaba	January	77	78	70	75
Green Bay	January	75	76	68	73
Muskegon	January	83	82	76	78
Chicago	January	78	80	70	75
Escanaba	July	83	80	65	69
Green Bay	July	87	86	59	64
Muskegon	July	85	83	57	61
Chicago	July	77	78	51	55
Escanaba	October	81	83	67	75
Green Bay	October	81	85	56	71
Muskegon	October	82	86	68	78
Chicago	October	73	80	51	78

humidities are generally higher than mid-day values in the summer and fall, but nocturnal values are typically higher in the warm season than in the cold season. The highest humidities occur in the morning (0700) in both January and October, but in July they occur at night (0100). The values also indicate that Muskegon, in a lake-effect area, has the highest relative humidity values in all hours in both January and October. In July, the lowest hourly values occur at Chicago, representative of the south, and the highest values occur at either Green Bay or Escanaba, indicating a north-to-south decrease in relative humidity in the summer.

Figure 31 presents the noontime average dewpoint temperature pattern around Lake Michigan for the year; the winter average pattern was presented in Figure 28c. In both patterns, there is a pronounced lake effect with annual average values indicating an increase of 1-2°C (1.8-3.6°F) on both sides of Lake Michigan. The net effect of Lake Michigan on the moisture content of the lower atmosphere is an increase extending 30-50 km (19-31 mi) east of the Lake in lower Michigan. Although some evaporation from the Lake occurs in summer, the surface dewpoint values at downwind lake stations do not indicate any increase. Theoretically, condensation should occur when the lake surfaces are colder than the dewpoint of the air passing over them. This is presumed to occur on the Lake in the spring and early summer but this phenomenon has not been directly measured. The average dewpoint temperature patterns for spring and summer show a clear latitudinal distribution with a gradient from north to south without lake effects. In summer, the average dewpoint temperature in the north is 17°C (63°F) as compared to 19°C (66°F) in the south.

The precipitation, evaporation, runoff, and groundwater values for the Lake Michigan region can be combined (algebraic sum) into a single value which is called the net basin supply of water to the Lake. Since the groundwater contributions to Lake Michigan are assumed to be negligible (Jones and Meredith, 1972) the net basin supply is precipitation minus evaporation (including evapotranspiration) plus runoff. The net basin supply values which were obtained by Jones and Meredith (1972) using 20-yr values of precipitation, evaporation, and runoff show an average annual value of 2400 m^3/sec (~84,750 ft^3/sec), or a net positive supply. The annual values calculated for each year range from a low of 250 m^3/sec (~8830 ft^3/sec) to a high of 4500 m^3/sec (~158,910 ft^3/sec). The average monthly values were all negative from September through December;

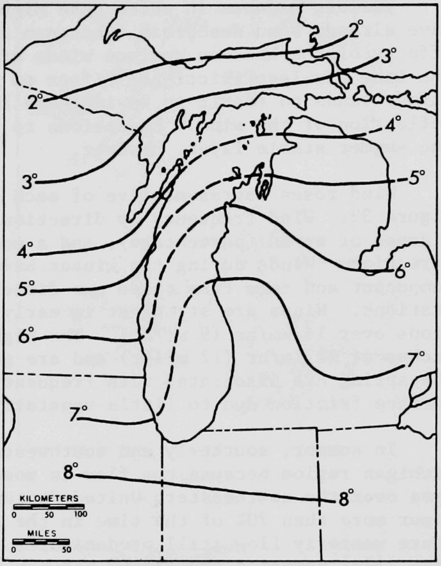


Fig. 31.

Average Annual Dewpoint Temperature Pattern, °C, at Noon (LST).

each value was more than 420 m^3/sec ($\sim$14,830 ft^3/sec). The values revealed a period of net water loss in the fall and early winter in Lake Michigan, then shifting to a period of large gain during the spring and early summer.

WINDS

Winds have a great influence on human activities and comfort. Excessive winds can produce high waves on Lake Michigan and a set-up (piling of water at the downwind portion of the Lake). This changes water levels with damage to marine installations and possible loss of life to boaters. When the wind stress subsides or changes direction, the lake water can oscillate back and forth and this phenomenon is known as a seiche. Wind shifts can also cause dramatic changes in the distribution of the surface-water temperature of Lake Michigan. Strong continuous winds from a single direction can transport warm water across to the lee side of the Lake and allow colder subsurface waters to rise on the windward side through upwelling. Such upwelling can lead to strong temperature gradients and the formation of fog over the colder water. The persistence of the wind and its speed have a great influence on power demands in both winter and summer. Winds are also particularly important in the ventilation of the Lake Michigan region, particularly for removing pollutants generated by the major urban areas and large power plants.

Wind speed and direction are continuously recorded at the eight major first-order airport stations in the region: Escanaba, Green Bay, Muskegon, Grand Rapids, Lansing, South Bend, Chicago, and Milwaukee. Wind vanes with cup anemometers that measure speed are generally located 10 m ($\sim$30 ft) above the surface. Direction and speed values are continuously recorded.

Various manners in which Lake Michigan affects wind direction and speed have already been described (Changnon and Jones, 1972). In general, the effects of the Lake on surface winds are considerable in all seasons because the Lake has less frictional effect on near-surface winds than the land. This effect tends to result in an increase in wind speeds and in some seasons a deflection of the wind. Exceptions to this general behavior can occur within the summer stable layer, however.

Wind roses representative of each season at four airports are shown in Figure 32. Wind frequency by direction (eight points of the compass), selected classes of speed (percentage), and a mean wind speed are listed for each direction. Winds during the winter have a major westerly and northwesterly component and come from those two directions nearly 40% of the time at all stations. Winds are strongest in early spring with mean speeds for all directions over 14 km/hr (9 mi/hr). The highest mean speeds in spring are in excess of 20 km/hr (12 mi/hr) and are generally westerly. Strong speeds in the spring are associated with frequent cyclonic storms and a minimum of land-surface friction due to little vegetative growth.

In summer, southerly and southwesterly winds predominate in the Lake Michigan region because the flow is most often controlled by a high-pressure area over the southeastern United States. Winds from the southwest and south occur more than 70% of the time in the region, other than at Grand Rapids where westerly flow still predominates in July. The October wind roses (Fig. 32d) reveal a transition between the cold and warm conditions in both speed and direction. The great temperature differences between air and water, plus the increase of cyclonic activity in fall, lead to fall wind speeds that are higher than those of summer. The prevailing direction in the fall tends to be southerly, although there is an increased frequency in west and northwest winds at all four stations. An over-lake wind climatology has never been developed.

Figure 33 presents seasonal patterns based on the mean wind speed (isotachs in km/hr); wind barbs show the prevailing wind direction. The wind speed pattern shows a general northwest-to-southeast increase in speeds, but with a lake-induced high of over 19 km/hr (12 mi/hr) superimposed on the pattern. Speeds are highest over the Lake and the eastern portion of the region (Odell, 1931). Wind directions in winter (Fig. 33a) are basically westerly in the western half of the region, with a shift to southwest in the eastern portion.

The summer wind pattern (Fig. 33b) shows that the Lake Michigan region is one of a general wind maximum. Speeds are highest over the Lake and lower Michigan. The prevailing flow is south to southwest in the southern and western portion of the region, but becomes more westerly at stations in the immediate lee of the Lake. Locations at the immediate western shore (not shown in Fig. 33b) have a prevailing easterly wind due to lake breezes. Prevailing flow in the northern portion of the region is westerly.

Wind speeds are often critical during excessively warm summer periods and cold winter periods because they affect energy usage. The frequency of excessive hourly temperatures in winter and summer associated with various wind speeds are summarized for three locations in Table 13. The situation with high winter winds during hours having temperatures below 0°C (32°F) is

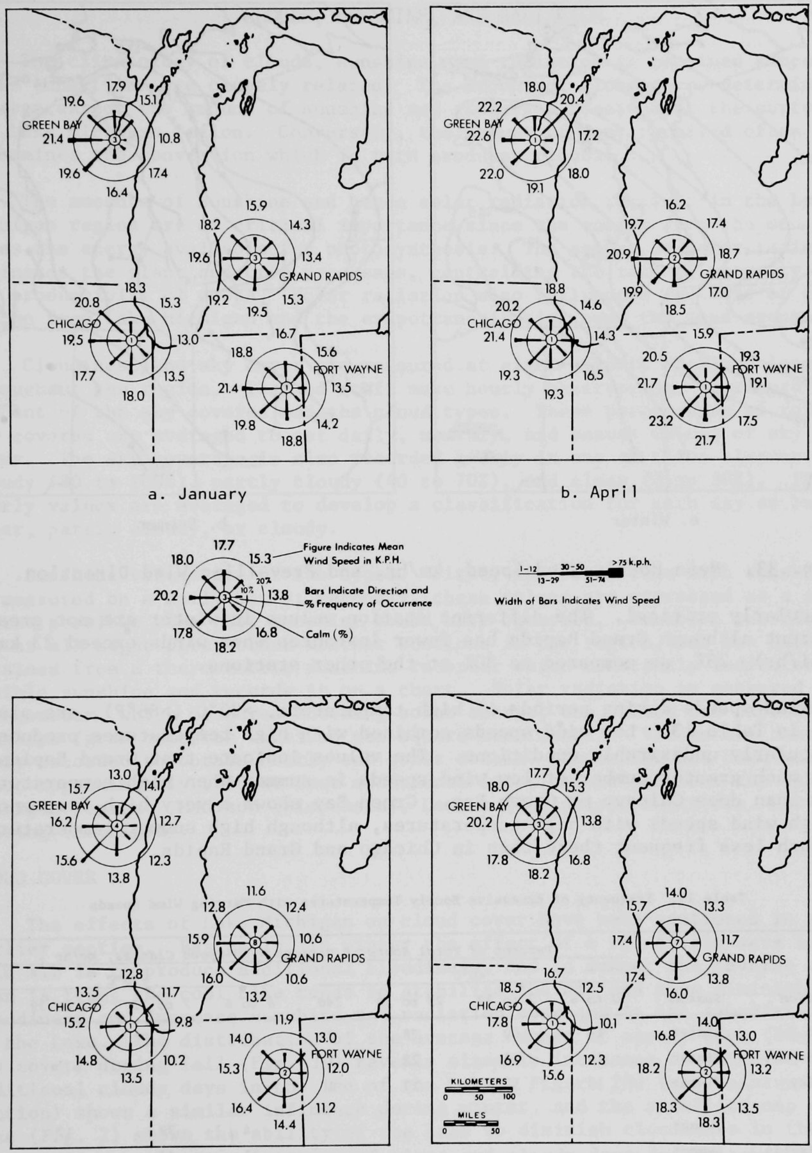
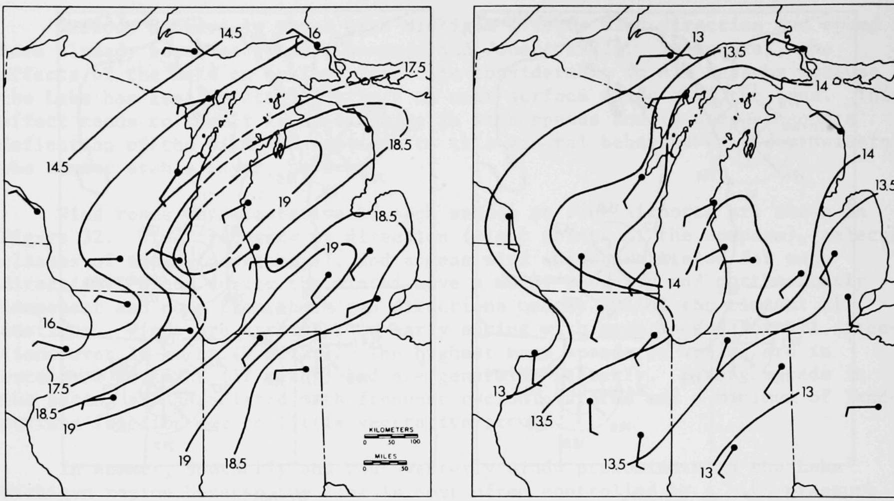


Fig. 32. Wind Roses at Selected Stations, 1951-1960. Modified from Phillips and McCulloch (1972) (with permission, see credits).



a. Winter b. Summer

Fig. 33. Mean Hourly Wind Speed, km/hr, and Prevailing Wind Direction.

particularly critical. The different station values in winter are not greatly different although Grand Rapids has fewer instances when winds exceed 23 km/hr (14 mi/hr), 23%, as compared to 30% at the other stations.

Wind speeds during periods of high temperature, >30°C (>86°F), are also shown in Table 13. Low wind speeds combined with high temperatures produce particularly undesirable conditions. The values indicate that Grand Rapids has a much greater number of low wind speeds in summer when high temperatures occur than does Chicago or Green Bay. Green Bay shows a very high frequency of high wind speeds with high temperatures, although high summer temperatures are much less frequent there than in Chicago and Grand Rapids.

Table 13. Frequency of Excessive Hourly Temperatures with Varying Wind Speeds

		Percent of Total Hours in Various Wind-Speed Classes, km/hr							
		<0°C				*>30°C*			
Location	*Season*	*0 to 6*	*7 to 22*	*23 to 39*	*≥40*	*0 to 6*	*7 to 22*	*23 to 39*	*≥40*
Chicago	Winter	10	60	28	2				
Grand Rapids	Winter	14	63	22	1				
Green Bay	Winter	13	57	29	1				
Chicago	Summer					4	79	17	0
Grand Rapids	Summer					11	67	21	1
Green Bay	Summer					3	47	46	4

CLOUDS, SUNSHINE, AND RADIATION

The climatology of clouds, sunshine, and radiation is combined since these conditions are closely related. The amount of cloud cover determines to a large extent the amount of sunshine and radiation received at the surface of the Lake Michigan region. Conversely, the amount of heat received often determines the convection which in turn produces clouds.

The amounts of sunshine and hence solar radiation received in the Lake Michigan region are of critical importance since the energy from the sun provides the energy available for photosynthesis. The amount of solar radiation dominates the plant and crop processes, controlling the rate of maturity and the productivity of crops. Solar radiation also influences the rate of evaporation from Lake Michigan and the evapotranspiration over the land areas.

Cloudiness and sky cover are measured at eight airport stations located throughout the region. Trained staff make hourly observations to record the percent of the sky covered and the cloud types. These percentages of total sky covered are averaged to get daily, monthly, and annual values of sky cover. The sky coverage is also recorded hourly in one of three classes: cloudy (80 to 100%), partly cloudy (40 to 70%), and clear (0 to 30%). These hourly values are averaged to develop a classification for each day as being clear, partly cloudy, or cloudy.

Sunshine values are of two types. First, the total time with sunshine is measured on a daily basis; secondly, these values are expressed as a percent of the possible time that sunshine could have occurred. Sunshine recorders are at all eight first-order weather stations in the region, and the data are obtained from a thermometric sunshine recorder which constantly indicates visible sunshine and records it on a chart. Solar radiation is measured on a pyranometer, which measures incoming solar energy; the values are expressed in Langleys (gram calories received per square centimeter). Values are continuously recorded to obtain hourly and other totals. Radiation has been measured since approximately 1950 at four additional locations in and near the Lake Michigan region: Madison (Wisconsin), Lemont (Illinois), Sault Ste. Marie and Lansing (Michigan).

CLOUD COVER

The effects of Lake Michigan on cloud cover have been mentioned in an earlier section. Basically, in winter the effect of a relatively warm Lake on cold air is to produce additional cloudiness, and in summer the reverse condition is true; the cool Lake tends to stabilize the air and thus diminish cloudiness and increase sunshine and radiation over and in the immediate lee of the Lake. The distribution of the average number of cloudy days (80-100% sky cover) during fall (Fig. 34) reveals sizeable increases of seven to ten additional cloudy days in the lee of the Lake. Figure 28d (see Moisture section) shows a similar influence during winter, and the satellite map of the Lake (Fig. 2) shows the ability of the Lake to diminish cloudiness in the summer. Average summer patterns of clear and cloudy days do not exhibit comparable downwind effects as shown for fall (Fig. 34); most of the reduced cloudiness is restricted to the Lake and just a few kilometers in the lee of the Lake.

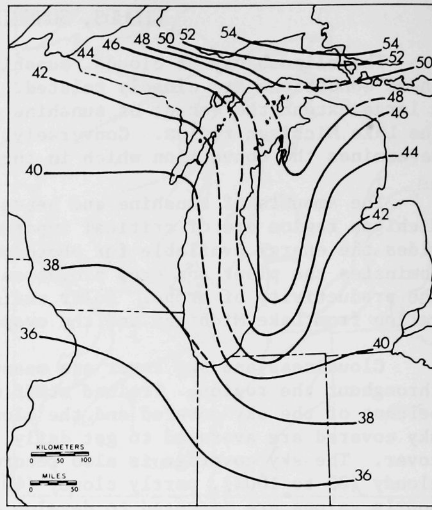


Fig. 34.

Pattern of the Mean Number of Cloudy Days in Fall.

Long-term shifts in cloudiness, sunshine, and radiation would have major effects on the general climate of the region. Figure 35 presents a five-year moving curve for the frequencies of cloudy days in Chicago from 1901 to 1973. A sizeable increase began in the 1920's, and the frequency of cloudy days appears to have reached a maximum around 1950. The increase between the decades of 1901-1910 and 1961-1970 is about 40% of the annual number of cloudy days. Historical data on cloudy-day conditions for Madison reveal a similar trend with an increase of 34% since 1901-1910. The seasonal increases at Chicago and Madison show the greatest changes in summer (+65%) and fall (+40%),

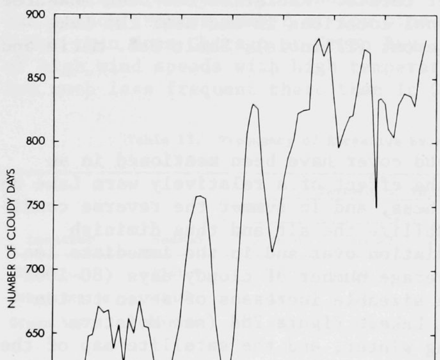


Fig. 35.

Five-Year Moving Totals of Number of Cloudy Days at Chicago, 1901-1973.

the two seasons that normally have the clearest skies. Cloudy days have also increased in the winter (+20%) and spring (+25%) at both stations. The impact of these changing trends on sunshine is revealed in Figure 36. A decrease in the hours of sunshine began in the 1920's at Chicago, and after stabilizing in the 1930's, the decrease dramatically resumed in 1950. Current sunshine values are 9% lower than those in 1901, which reveals that there has been an appreciable change in the Lake Michigan region in cloudiness, sunshine, and presumably in solar radiation.

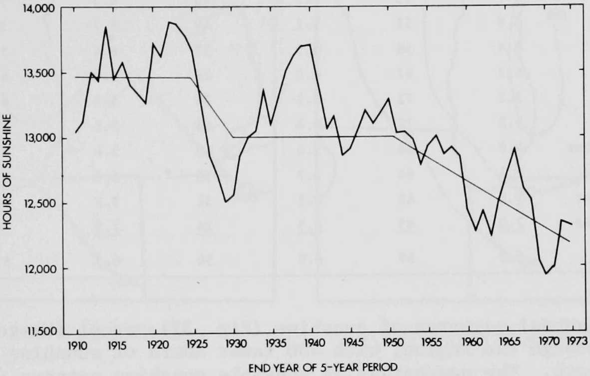


Fig. 36. Five-Year Moving Totals of Number of Hours of Sunshine at Chicago, 1901-1973.

Table 14 presents average monthly and annual statistics for sky cover and percent of possible sunshine at three widely separated stations in the region: Chicago, Grand Rapids, and Green Bay, (U. S. Dep. Commer., 1966a). They show a marked tendency for more cloud cover in the winter and less in the late summer and early fall. The values also reflect the combination of lake and latitudinal effects on clouds and sunshine. For instance, Grand Rapids has greater sky cover and less sunshine than the other stations from November through May. However, in the summer and fall seasons latitudinal effects predominate with more cloud cover and less sunshine at the more northerly station, Green Bay, and the least amount of cloudiness at Chicago.

SUNSHINE

The stabilizing of summer convection by the Lake is reflected in the summer season increases in sunshine from west-to-east across the Lake. During summer, west-to-east values (of percent of possible sunshine across Lake Michigan) range from 67 to 69% across the south end and from 63 to 66% across the northern portions of the Lake. The lake effects that bring added cloudiness in winter result in less sunshine over the Lake and the shore stations to the east (Table 14). Shore stations downwind of Lake Michigan receive 25 to 30% less sunshine in winter than stations at the same latitude to the west of the Lake.

Table 14. Monthly Values of Sky Cover and Possible Sunshine
(Data from U. S. Dep. Commer., 1966a)

	Chicago		*Grand Rapids*		*Green Bay*	
Month	*Mean Sky Cover*	*% Possible Sun*	*Mean Sky Cover*	*% Possible Sun*	*Mean Sky Cover*	*% Possible Sun*
January	7.2	43	8.6	28	6.7	47
February	6.9	48	8.0	37	6.5	51
March	6.7	53	7.5	46	6.3	56
April	6.8	52	7.1	49	6.7	51
May	6.4	58	6.5	57	6.4	58
June	6.2	67	6.2	66	6.0	64
July	5.1	72	5.5	70	5.6	64
August	5.2	70	5.4	66	5.6	62
September	4.9	68	5.4	63	5.4	60
October	5.1	64	5.7	58	5.6	57
November	7.1	43	8.1	31	7.2	40
December	7.0	43	8.5	24	7.3	30
Annual	6.2	59	6.9	50	6.3	55

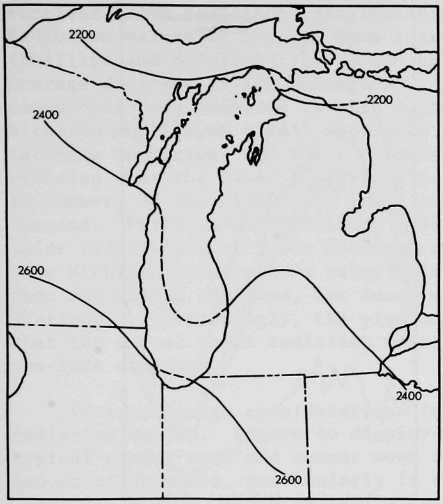
The mean annual patterns of sunshine (Fig. 37) reveal the general latitudinal trend through the region, with 400 fewer hours of sunshine in the north than in the south. The percentage of possible sunshine pattern (Fig. 37b) reveals the lake-related fall and winter season effects, with less than 50% of possible sunshine in lower Michigan along the Lake. Otherwise, regional values decrease from 60% in the southwest to 50% in the north. Seasonal patterns of the percent of possible sunshine (Fig. 38) reveal a general latitudinal distribution in summer with no indication of lake effects. However, the winter pattern shows that the possible sunshine is decreased dramatically from 40% along the west side of the Lake to less than 30% on the east side of the Lake.

SOLAR RADIATION

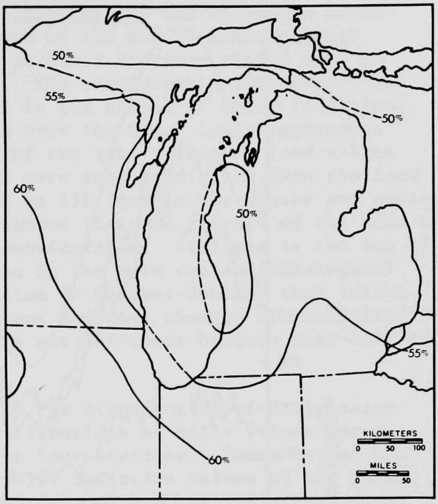
In general, the average annual values of daily solar radiation in the Lake Michigan region reveal no pattern. The annual averages are 335 Langleys per day at Sault Ste. Marie, 325 at Madison, 331 at Lansing, and 348 at Lemont; the regional daily average is 335 Langleys.

The annual cycle of solar radiation for the four stations (Fig. 39) indicates a peak in mid-summer and a low in mid-winter (Baker and Klink, 1975). Comparison of the average curves (numbered 2, 3, and 4) reveals little difference in the measured radiation in the warm season, but there is considerable difference in the cold season. January solar radiation values, which are typical of the winter values, vary from 150 Langleys/day in the southwest section (Lemont) to less than 130 in the eastern portions (East Lansing and Sault Ste. Marie) of the region.

The expected latitudinal gradient of solar radiation on a winter and annual basis is not evident because of other influences including local variations of major cities, elevation, regions of varying snow cover, and lake effects. Urban air pollutants certainly account for large local variations of

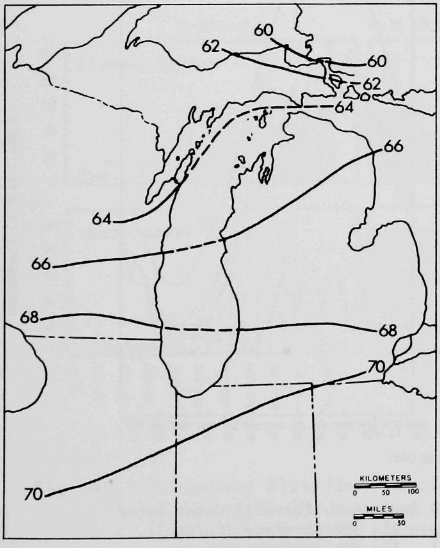


a. Total hours of sunshine

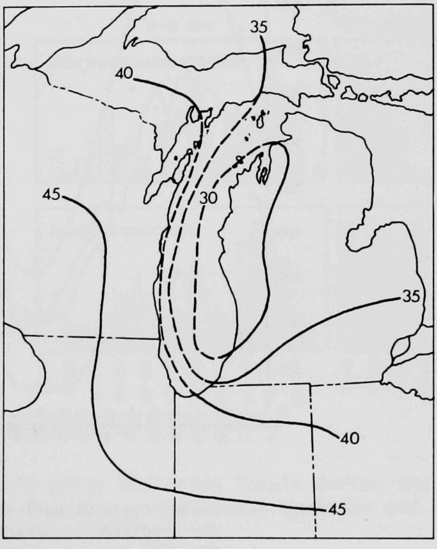


b. Percentage of possible sunshine

Fig. 37. Mean Annual Sunshine Patterns.



a. Summer



b. Winter

Fig. 38. Seasonal Patterns of Percent of Possible Sunshine.

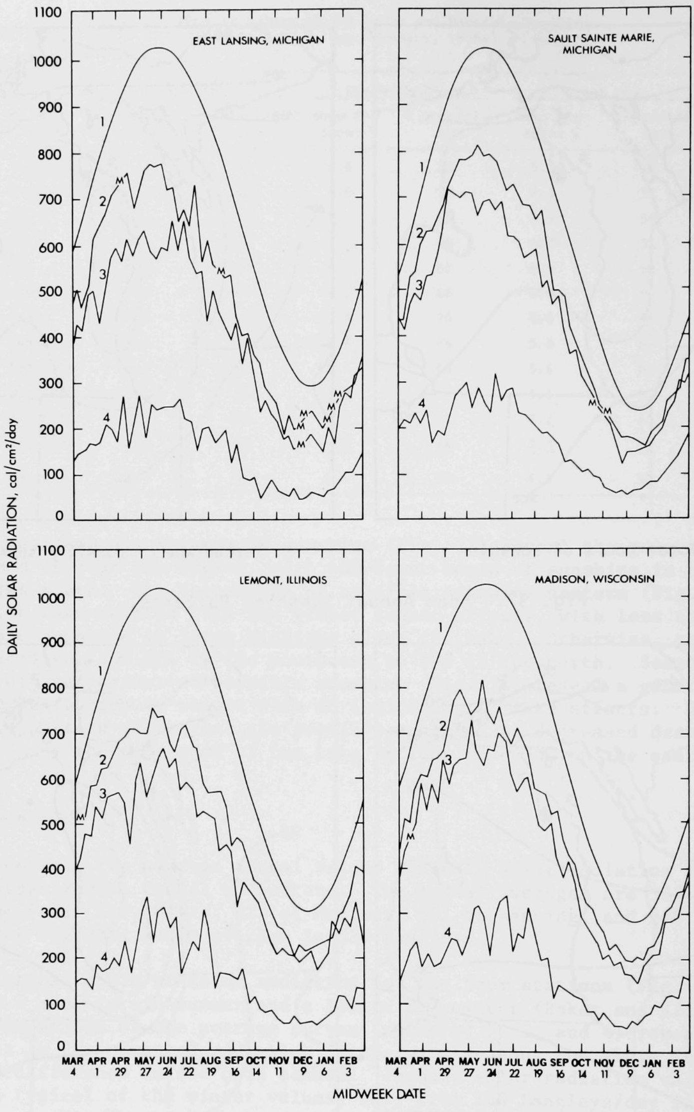


Fig. 39. Annual Cycle of Daily Solar Radiation (Curve 1) Under Three Sky Conditions: Clear (Curve 2), 50% Coverage (Curve 3), and 100% Coverage (Curve 4). The M's indicate missing data; the values were partly estimated from other stations. Slightly modified from Baker and Klink (1975) (with permission, see credits).

received solar radiation, particularly in the Chicago and Milwaukee areas. Radiation values at Toronto show a decrease of 11% due to urban effects (Phillips and McCulloch, 1972) and those at other American cities show an average decrease of 22% (Changnon, 1973). The considerable lake effect on cloud cover and sunshine is also apparent in the amount of solar radiation. Richards and Loewen (1965) used ship data over the Great Lakes to measure incoming radiation, and their comparison of the lake values to land values revealed that the lakes received 9 to 28% more total radiation than the land in summer, 30 to 40% more in fall, and 10 to 15% less in the winter and spring seasons. Phillips and McCulloch (1972) showed that the effects of the Lake on solar radiation over lower Michigan are considerable. Stations in the lee of Lake Michigan receive more solar radiation in the warm season (May-August) than far inland stations, but less radiation in October-January than inland stations. Interestingly, the plus and minus seasonal changes are nullified so that the annual solar radiation values are not different between near-lake and non-lake stations.

Various design considerations involve the distribution of daily solar radiation values. Figure 40 displays distributions of daily values for a typical winter week and summer week at the four stations. These reveal the amount of skewness, particularly in the solar radiation values of the summer week, 21-27 June, which typically has many days with large radiation values (greater than 600 Langleys/day), but also has many days with small radiation values. The lake effect on cloudiness is most evident at Sault Ste. Marie where there are many more summer days with low values of radiation than at Madison or Lansing.

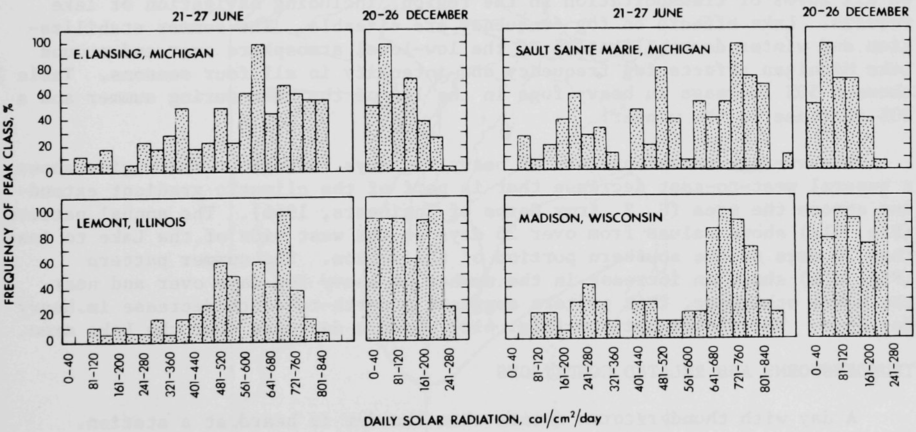


Fig. 40. Frequency Distribution of Daily Solar Radiation Totals during the Weeks of 21-27 June and 20-26 December. Modified from Baker and Klink (1975) (with permission, see credits).

WEATHER PHENOMENA

Certain weather phenomena that affect human activities in the Great Lakes region include fog, thunderstorms and their products (including hail and tornadoes), and visibility. Fog and limited visibility restrict transportation, and thunderstorms produce valuable amounts of annual precipitation as well as damage through severe storm activity.

Each of these phenomena is measured at the first-order stations of the National Weather Service. In addition, thunderstorms and hail are recorded at several of the cooperative substations manned by volunteers. At the first-order stations, trained staff make hourly observations of each of these phenomena to discern their existence. Their occurrences, if they last for at least five minutes and occur at any given hour, are used to declare the day as one with the given event.

FOGS

Fogs are caused by a variety of conditions. Radiation fogs, which occur commonly in the nights of spring and fall during calm conditions, are caused by radiational cooling of the land. Advection fogs form when warm air moves over cold surfaces, a condition that occurs during the winter and spring. Steam fogs occur over the Lake in winter when very cold air combines with lake evaporation.

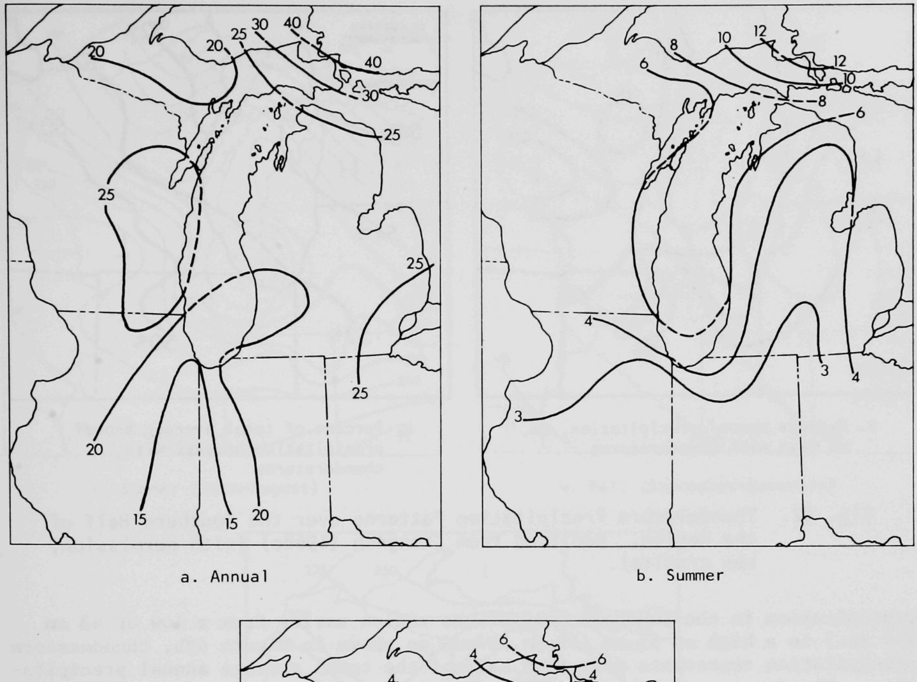
Heavy fogs [conditions when the horizontal visibility is less than 150 m (500 ft) due to water droplets or ice crystals] have major detrimental effects on all forms of transportation in the region, including navigation of lake vessels. Lake effects on fog frequency are sizeable. The summer stabilization and winter destabilization of the low-level atmosphere over and around Lake Michigan affects fog frequency and intensity in all four seasons. Table 2 shows a 50% increase in heavy fogs in the lee of the Lake during summer and a 20% decrease in the winter.

The average annual pattern of heavy fog days throughout the region shows a general west-to-east decrease that is part of the climatic gradient extending across the area (U. S. Army Corps of Engineers, 1966). The annual pattern (Fig. 41a) shows values from over 25 days on the west side of the Lake to less than 20 days in the southern portion of the region. The summer pattern (Fig. 41b) shows an increase in the number of heavy fog days over and near the Lake; otherwise, this pattern suggests a north-to-south decrease in heavy fog days. The winter pattern (Fig. 41c) shows a decrease over the Lake area.

THUNDERSTORMS AND RELATED CONDITIONS

A day with thunderstorms occurs when thunder is heard at a station. Thunderstorms are generally caused by two conditions: (*i*) frontal passages through the region associated with cyclonic storms, or (*ii*) localized heating during the warm months which leads to convection sufficient to initiate isolated or air mass thunderstorms.

Thunderstorms are an extremely important weather phenomenon in the Great Lakes region (Changnon, 1968a). The importance of precipitation produced by thunderstorms is revealed in Figure 42 (Changnon, 1968c). Thunderstorm

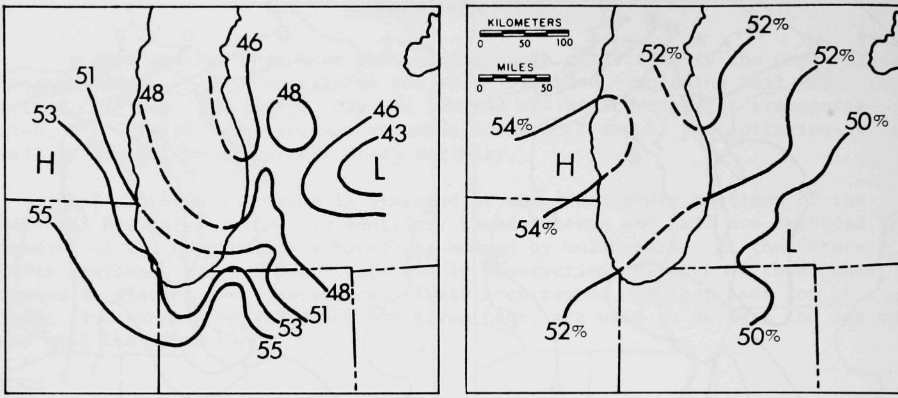


a. Annual

b. Summer

c. Winter

Fig. 41. Patterns of the Average Number of Days with Heavy Fog.



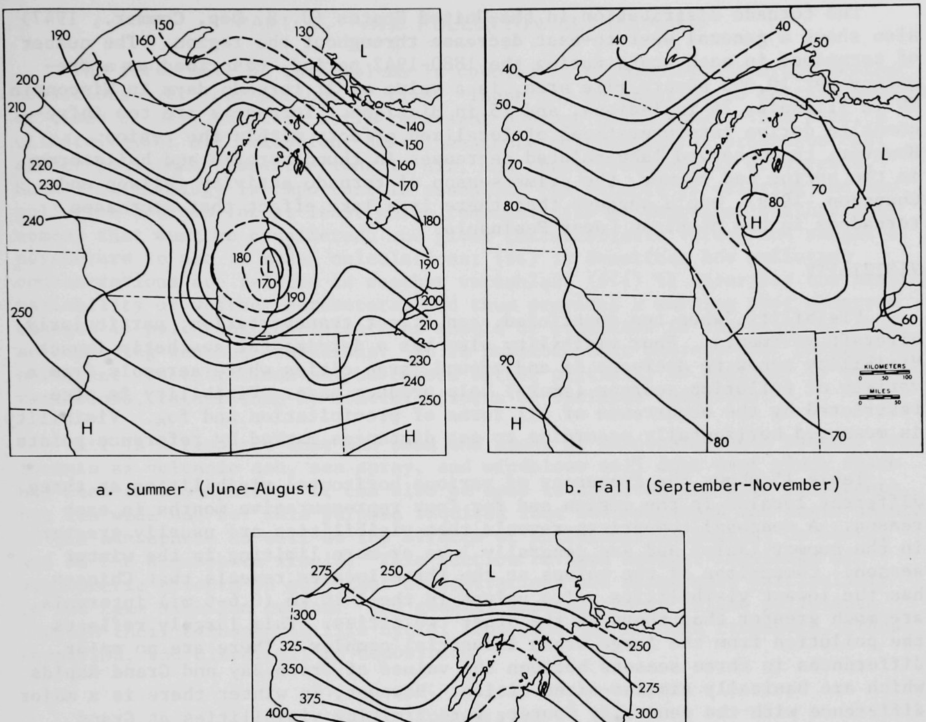
a. Average annual precipitation, cm, on days with thunderstorms

b. Percent of total average annual precipitation on days with thunderstorms

Fig. 42. Thunderstorm Precipitation Patterns over the Southern Half of the Region. Modified from Changnon (1968c) (with permission, see credits).

precipitation in the southern half of the region varies from a low of 43 cm (17 in.) to a high of 55 cm (22 in.), and as shown in Figure 42b, thunderstorm precipitation represents more than half of the total average annual precipitation. Thunderstorms also are responsible for most of the damaging severe weather of the warm season, producing lightning, hailstorms, occasional tornadoes, and damaging straight-line winds. Because thunderstorms and their associated phenomena are strongly related to heating and moisture in the warmer seasons, Lake Michigan greatly affects thunderstorm activity. In summer when the Lake is relatively cold, thunderstorms are diminished over the Lake and beyond it; in the fall and early winter when the Lake is relatively warm, it enhances thunderstorm activity (Changnon, 1966a).

The pattern of the average number of thunderstorm days during a ten-year period (Fig. 43c) shows a basic latitudinal distribution. The net effect of the Lake is noticeable with the area of lower frequencies (350 days) in the south and an area of greater frequencies in the upper Lake area. The summer average map (Fig. 43a) shows that the Lake decreases thunderstorm activity, particularly at the southern end of the Lake where values of 170 days exist as opposed to 220 to 240 days just west of the Lake. As shown in Table 2, the decrease in thunderstorm activity at the south end of the Lake in summer is about 10% as opposed to an average increase of 25% in fall. In the fall (Fig. 43b), the Lake increases activity (Changnon, 1966a) leading to sizeable increases, particularly over the upper portion of the Lake Michigan region. Some areas in the lee of Lake Michigan have an increase of 50% in average fall thunderstorm frequency due to the Lake (Fig. 6). The winter thunderstorm pattern shows a slight increase in activity east of the Lake, and the spring average pattern is latitudinal.



a. Summer (June-August)

b. Fall (September-November)

c. Annual

Fig. 43. Number of Thunderstorm Days in an Average 10-Year Period. Slightly modified from Changnon (1966a) (with permission, see credits).

There is a basic west-to-east decrease in the climatic pattern of hail through the region, from three days at points in the southwestern portion to less than two days per year in the northeast. Superimposed on this are lake effects on hail activity. There is a localized reduction (30%) of hailstorms in the spring and summer (Table 2), but a major increase (100%) in hail during the fall season. Hail days in the fall, west of Lake Michigan, are three per ten years, as opposed to nine per ten years in the lee of the Lake.

The tornado distribution in the United States (U. S. Dep. Commer., 1947) also shows a general west-to-east decrease throughout the region. The number of tornadoes in each state during the 1880-1942 period, described as a frequency per 10,000 square mile area, is a value of 21 tornado days in Wisconsin, 29 in Illinois, 26 in Indiana, and 15 in Michigan. Tornadoes are too infrequent to derive interpretations of localized effects within the region. However, the observed lake-related decreases in thunderstorms and hailstorms in the spring and summer, the prime season of tornado activity (Wilson and Changnon, 1969), would suggest that there is a lake effect that decreases tornadoes in the Michigan Lower Peninsula.

VISIBILITY

Visibility, when too restricted, can affect transportation, particularly aircraft movements. Poor visibility also has a detrimental aesthetic impact. Visibility tends to decrease in and around large cities where aerosols from a variety of pollution sources (smoke) help produce haze. Visibility is also restricted by the occurrence of all forms of precipitation and fog. Visibility is measured horizontally according to set distances marked by reference points.

Table 15 shows the frequency of various horizontal visibilities at three different locales in the region and for four representative months in each season. A seasonal comparison reveals that visibilities are usually greater in the summer (July) and are generally less or more limiting in the winter season. Comparison of the values at the three locales reveals that Chicago has the lowest visibilities. Its values in the 1-10 km (0.6-6 mi) intervals are much greater than those at the other two cities. This largely reflects the pollution from the large urban industrial complex. There are no major differences in three seasons between the values of Green Bay and Grand Rapids which are basically similar-sized cities. However, in winter there is a major difference with the generally poorer, more limiting visibilities at Grand Rapids. This is likely due to the lake-increased winter precipitation through that region.

Table 15. Frequency of Visibilities During 1951-1960 at Selected Stations

		Percent of Total Hours with Visibilities in Distance Intervals, km			
Location	*Month*	*< 1*	*1 to 4*	*4 to 10*	*10 to 24*
Green Bay	January	4	9	11	76
Grand Rapids	January	3	15	19	63
Chicago	January	4	15	36	46
Green Bay	April	4	4	7	85
Grand Rapids	April	1	4	11	84
Chicago	April	1	8	30	61
Green Bay	July	2	2	7	89
Grand Rapids	July	1	2	8	89
Chicago	July	1	4	29	66
Green Bay	October	3	7	10	80
Grand Rapids	October	1	3	11	85
Chicago	October	1	7	29	64

PART 2. AIR POLLUTION CLIMATOLOGY

The first part of this volume is devoted to climatology--average weather conditions over long periods of time. These may be specific to certain seasons or times of day, but they still represent average conditions. This part, a climatology of air pollution, describes those meteorological processes that affect pollutant concentrations in air, and their frequency of occurrence. Such a climatology is important in assessing the effects of existing and new pollution sources for at least three reasons: (*i*) it describes weather phenomena that must be considered, and gives characteristic values and ranges of parameters to use in model calculations; (*ii*) it describes how pollutant concentrations are related to weather variables; (*iii*) it describes the natural variability of weather parameters, and thus provides a warning that observed changes in pollutant concentrations should be evaluated in the light of their accompanying weather conditions. It is possible that year-to-year changes in pollutant concentrations may be caused either partially or entirely by weather variations, rather than by control efforts or variable emissions.

Air is a resource that has been the agent of dispersing such natural pollutants as volcanic ash, sea spray, and windblown soil dust ever since there has been an atmosphere. It can also be used to disperse man-made pollutants, but its wide use for this purpose requires that we understand the basic nature of the atmosphere as well as the effects of pollutants on health, on biota, and on the atmosphere itself. This section reviews current knowledge of atmospheric effects on pollutant concentrations and dispersal, particularly in the Lake Michigan region. The general approach is to follow pollutants through their atmospheric life cycle, from emission through transport, transformation, and dispersal, to deposition.

AIR QUALITY

Any discussion of air quality should include some consideration of emissions. After all, emitted pollutants are acted on by meteorological processes to produce air quality. Specification of emissions is possible, however, only to a limited degree. Annual man-made emissions of the major pollutants have been published for each state and Air Quality Control Region (EPA, 1973b). However, "natural" emissions such as wind-blown soil dust and biologically-produced sulfur compounds are not well established. Some estimates have been made for the whole earth (Friend, 1973), but estimates of natural emissions on the scale of cities or states are not now available.

This section begins with a presentation of known man-made emissions of total suspended particulate matter (TSP), SO_2, and NO_x (EPA, 1973b). Similar emission data have been published by the Environmental Protection Agency (1973b) for CO and hydrocarbons. Following our look at the national and regional distribution of emissions, we consider regional measurements of pollutant concentrations. These concentrations are a measure of the air quality produced by meteorological processes acting on emitted pollutants.

The following pollutants are discussed: TSP, SO_2, NO_2, CO, O_3, hydrocarbons, and trace metals. Whenever possible, concentrations are presented for locations in a wide range of population densities, from remote areas to central cities.

EMISSIONS

National patterns of emission strength (metric tons/km^2/year) are shown in Figures 44, 45, and 46 for TSP, SO_2, and NO_x, respectively (EPA, 1973b). Overall patterns for these three pollutants are rather similar; each shows considerably greater emission rates in the eastern half of the country than the western half. In general, the highest ranges of emission rates occur in and near large cities.

Most of the states surrounding Lake Michigan have TSP emissions in the range of 2-15 tons*/km^2. Areas of lower emission rates exist over the Lake and in central Wisconsin and western Indiana. A large area of emission rates over 15 tons/km^2 is present in Illinois, southwest of the Lake.

Except for the Lake itself, the SO_2 emission rates in the Lake Michigan states range from 1-25 tons/km^2. A large area of the southwest lakeshore, including the large population centers of southeast Wisconsin, northeast Illinois, and northwest Indiana, has rates over 25 tons/km^2. More distant

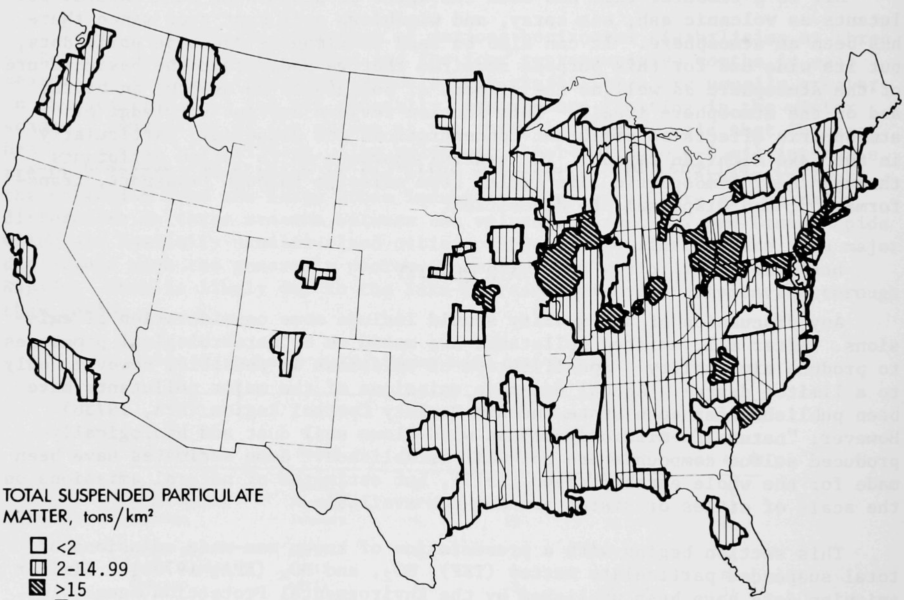


Fig. 44. National Distribution of Particulate Matter Emissions Averaged over Each Air Quality Control Region. Modified from EPA (1973b).

**All references to "tons" in this report are to metric tons, 10^3 kg. [Short tons (English unit) = 2000 lb; 1 metric ton = ∿1.1 short tons; 1 metric ton/km^2 = ∿0.4 short ton/mi^2.]*

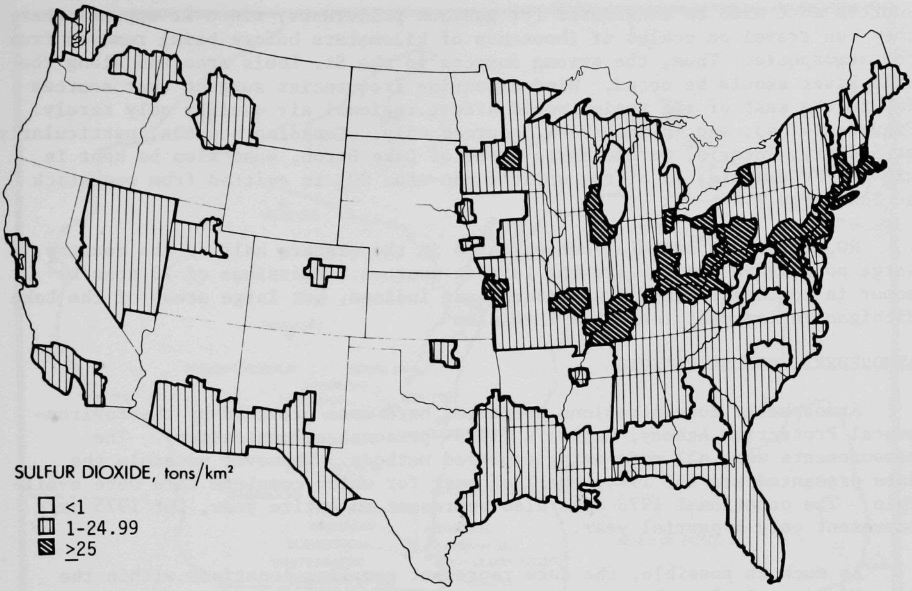


Fig. 45. National Distribution of Sulfur Dioxide Emissions Averaged over Each Air Quality Control Region. Modified from EPA (1973b).

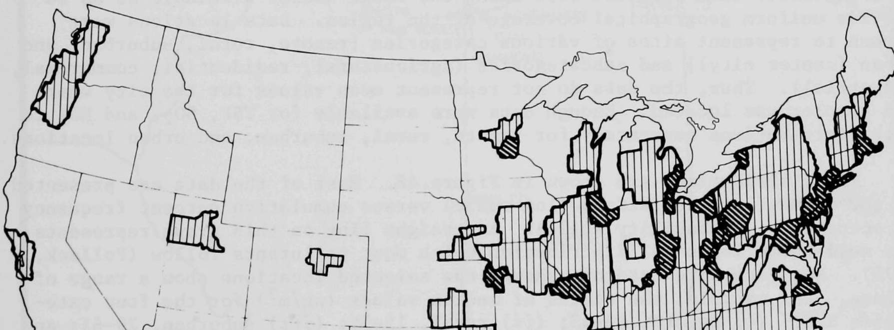


Fig. 46. National Distribution of Nitrogen Oxide Emissions Averaged over Each Air Quality Control Region. Modified from EPA (1973b).

sources must also be considered for gaseous pollutants, since it appears that they can travel on scales of thousands of kilometers before being removed from the atmosphere. Thus, the strong sources in the St. Louis area and along the Ohio River should be noted. Wind direction frequencies suggest that sources far to the east of the region would affect regional air quality only rarely. Figures 44, 45, and 46 show U. S. sources only. Canadian sources, particularly at Sudbury, Ontario, on the north shore of Lake Huron, must also be kept in mind. For example, 1% of the world's man-made SO_2 is emitted from one stack at Sudbury.*

NO_x emissions are also concentrated in the eastern half of the country. Large population centers are the largest sources. Emissions of 20 tons/km^2 occur in northeast Illinois and northwest Indiana, but large areas of the Lake Michigan region emit less than 2 tons/km^2.

ATMOSPHERIC CONCENTRATIONS

Atmospheric concentrations presented here were provided by the Environmental Protection Agency, Region V (1975--personal communication). The measurements were all made using approved methods. Whenever possible the data presented are for 1974, the last year for which complete data were available. The occasional 1973 data also represent an entire year, but 1975 data represent only a partial year.

As much as possible, the data represent sampling locations within the Lake Michigan Basin. However, it was necessary to include some data from outside the Basin to properly illustrate airborne concentrations in air approaching the region. A map of sampling sites is given in Figure 47. In general, sites were selected from among the large number available so as to provide uniform geographical coverage of the region. Data locations were chosen to represent sites of various categories [remote, rural, suburban, and urban (center city)] and subcategories (agricultural, residential, commercial, industrial). Thus, the data do not represent mean values for the city where the sampler was located. Enough data were available for TSP, SO_2, and NO_2 to plot distributions separately for remote, rural, suburban, and urban locations.

TSP distributions are shown in Figure 48. Most of the data are presented in the form of concentrations (log scale) versus cumulative percent frequency of occurrence (probability scale). A straight line on this graph represents the well-known lognormal distribution which most pollutants follow (Pollack, 1975). For each site category shown, the selected locations show a range of values. For example, the ranges of median values (μg/m^3) for the four categories are: (*i*) remote, 13-45; (*ii*) rural, 15-55; (*iii*) suburban, 29-61; and (*iv*) urban, 42-124. The large degree of overlap is illustrated by the fact that the smallest urban median is less than the largest remote median. Nevertheless, there is a general trend toward increasing concentrations moving from remote to urban areas, as is expected. At the remote and rural locations, the sites in northern Wisconsin and upper Michigan show the lowest overall concentrations. At urban locations, concentrations tend to be larger in the larger cities.

**The 351 m (∿1150 ft) stack at Sudbury emits an average of 4000 tons SO_2/day, or 1.46 × 10^6 tons/yr (Muller and Kramer, 1976--in press). Kellogg et al. (1972) have estimated world production of SO_2 by man at 100 × 10^6 tons/yr.*

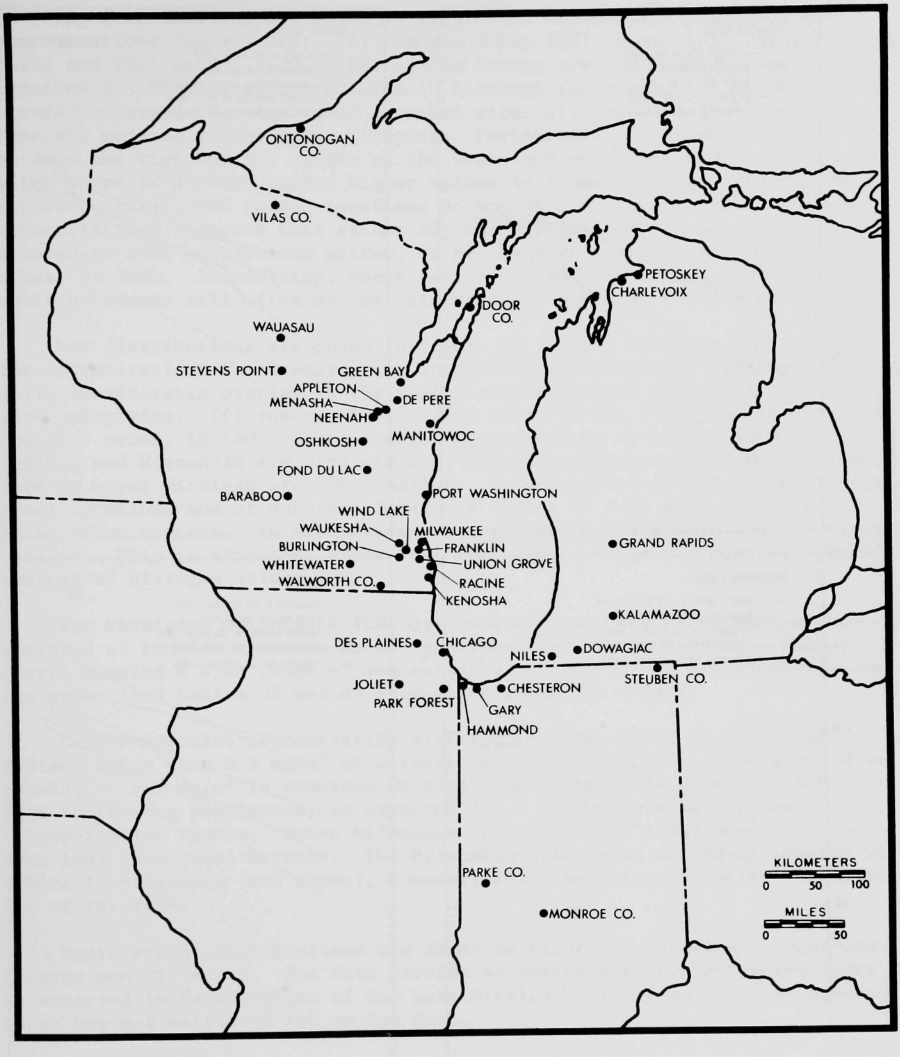


Fig. 47. Sampling Sites for which Data are Presented in Part 2, Air Pollution Climatology.

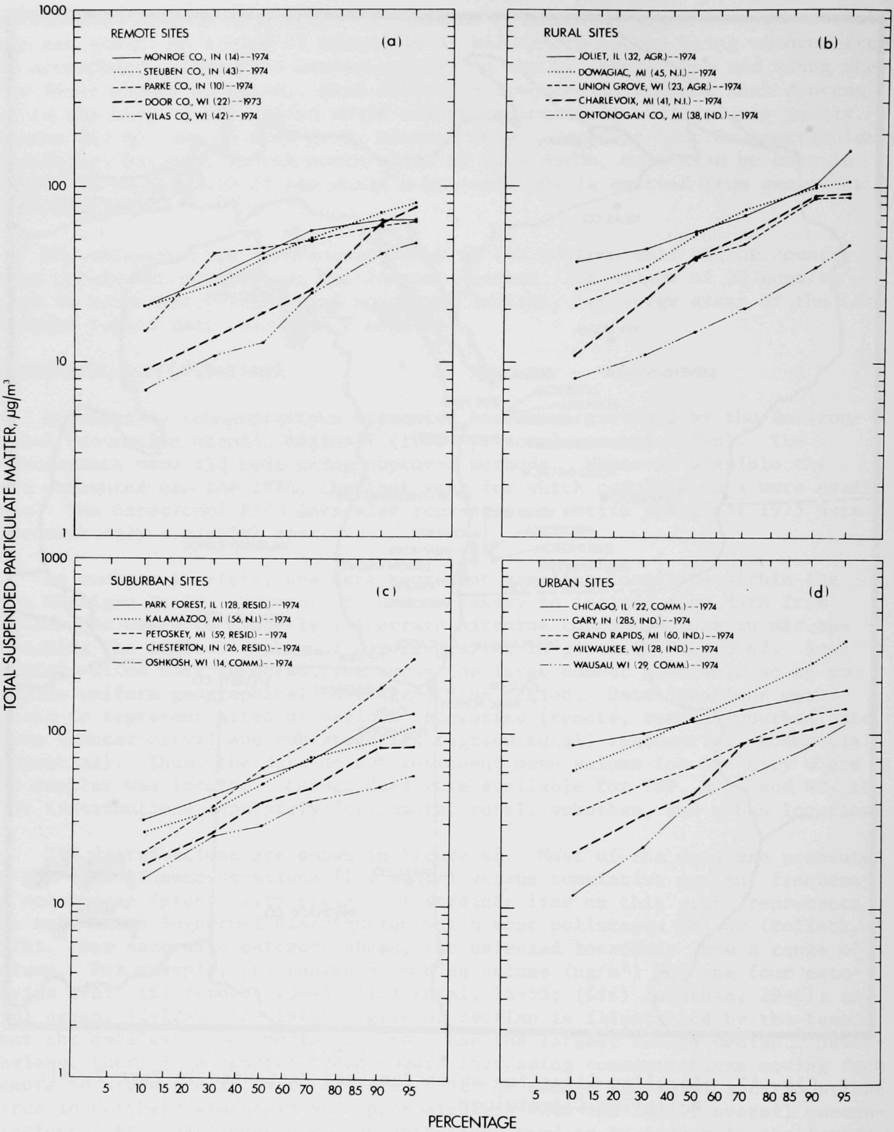


Fig. 48. Distribution of Total Suspended Particulate Matter Concentrations at Selected Sites Using the 24-hr Hivol Gravimetric Method. Urban sites were in center of city. Format: Site (no. of samples, site subcategory)--year sampled. Subcategories: Agr. = agricultural; N.I. = subcategory not indicated; Ind. = industrial; Resid. = residential; Comm. = commercial. Data from EPA, Region V (1975--personal commun.)

SO_2 distributions are shown in Figure 49. Respective ranges of median concentrations ($\mu g/m^3$) are: (*i*) remote, 9-13; (*ii*) rural, 2-8; (*iii*) suburban, 3-18; and (*iv*) urban, 3-20. There is no strong trend for increasing concentrations in the more populated areas. Although the lowest median occurred at a rural site and the highest at an urban site, all remote medians are larger than all medians in the rural category. Furthermore, the remote medians fall between the high and low values at the urban and suburban sites. Among urban sites there is a trend toward higher values in larger cities. The fact that suburban, rural, and remote locations do not show distinctly smaller overall concentrations suggests that either SO_2 has a relatively longer lifetime in the atmosphere than particulate matter, or SO_2 sources are not confined to urban areas, or both. In addition, where tall-stack sources are located in cities, their effluents will often not be detectable at the ground for some distance.

NO_2 distributions are shown in Figure 50. Again there is a general trend for concentrations to increase with increasing urbanization, although there is still considerable overlap in the median concentrations ($\mu g/m^3$) of the four site categories: (*i*) remote, 12-17; (*ii*) rural, 6-52; (*iii*) suburban, 11-70; and (*iv*) urban, 18-140. Concentration distributions at remote sites in Indiana and Wisconsin are very similar, although concentrations at the rural site in upper Michigan are even smaller. Concentration levels at the remaining rural locations and at suburban locations appear to vary with proximity to large urban centers. In urban areas, concentration and population are closely related. This is expected, since fuel combustion and transportation are major sources of nitrogen oxides.

The remaining pollutants (CO, O_3, hydrocarbons, and trace metals) are measured at too few sites to permit grouping results by location. Single charts showing a wide range of concentration distributions are presented for the gases, and tables of median values are given for metals.

Carbon monoxide concentration distributions are shown in Figure 51. Medians range from 0.5 mg/m^3 at a rural agricultural site near Baraboo, Wisconsin, to 6.9 mg/m^3 in downtown Chicago. Concentrations generally increase with increasing population, as expected for a pollutant with a primarily transportation source. Urban Milwaukee concentrations are anomalously low, even less than rural Baraboo. The Milwaukee site shown agrees in general with others in Milwaukee (not shown), however, which appears to confirm the validity of the data.

Hydrocarbon concentrations are shown in Figure 52 for single locations in Chicago and Milwaukee. The data provide an approximate concentration level to be expected in large cities of the Lake Michigan region, but further generalizations are not warranted for so few data.

Ozone concentrations in the region are summarized in Figure 53. Median concentrations range from 10 to 76 $\mu g/m^3$, with the highest medians at rural and remote sites. At first glance, this is somewhat unexpected, but high concentrations have also been observed in rural areas in New York (Stasiuk and Coffey, 1974) and O_3 concentrations were found to increase with distance in a Virginia power plant plume (Davis *et al.*, 1974). These seemingly anomalous results stem from the fact that O_3 is a secondary pollutant; *i.e.* it is produced in the atmosphere by chemical reactions involving sunlight and several primary pollutants. Maximum concentrations occur after a finite time interval during which the pollutants can be carried to rural locations by the wind.

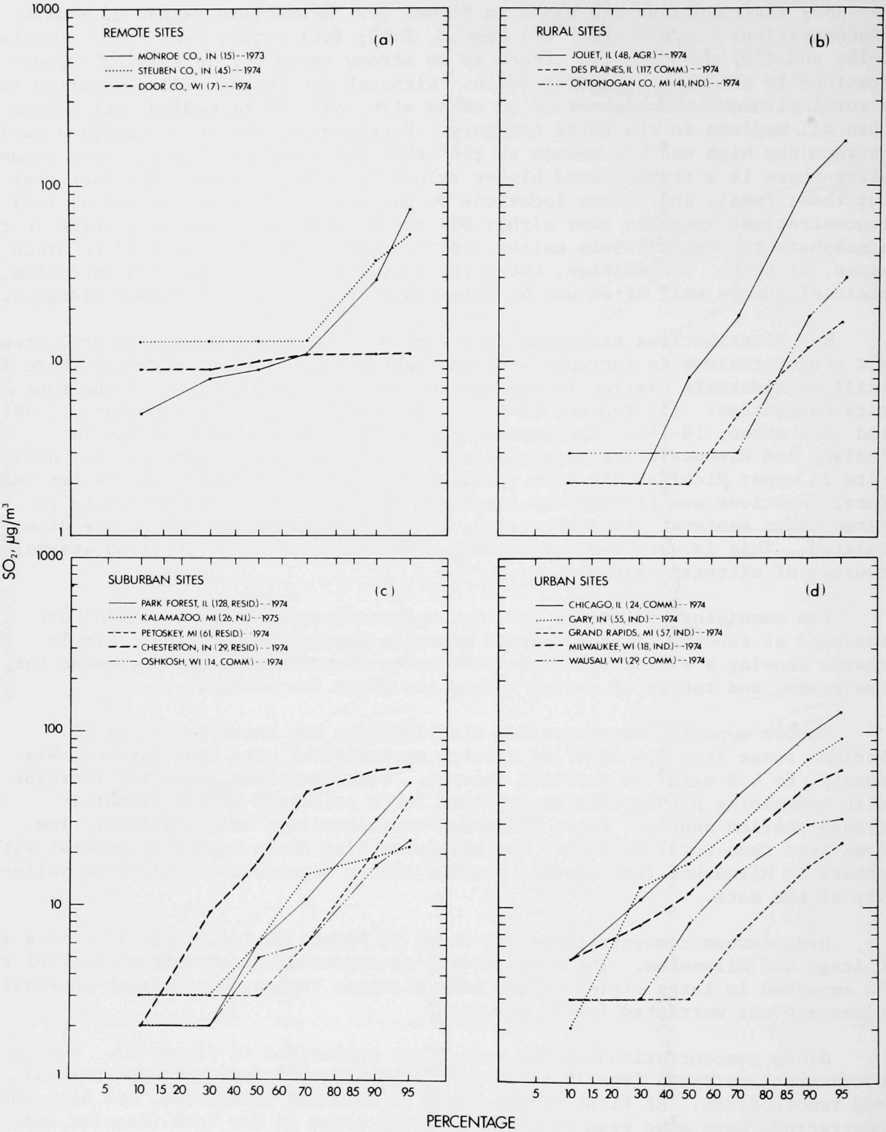


Fig. 49. Distribution of Sulfur Dioxide Concentrations at Selected Sites Using the 24-hr Bubbler, Pararosaniline-Sulfamic Acid Method. Data from EPA, Region V (1975--unpublished). Format and abbreviations are described in Figure 48.

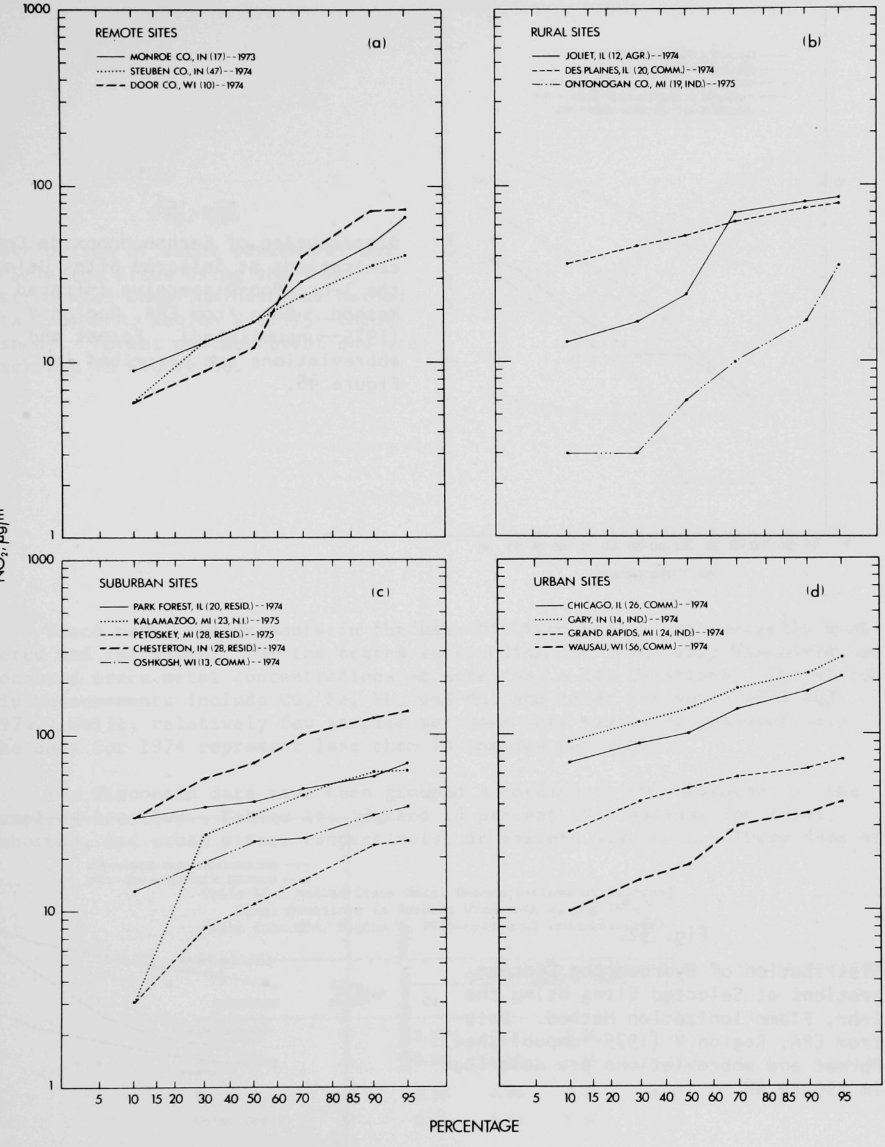


Fig. 50. Distribution of Nitrogen Dioxide Concentrations at Selected Sites Using the 24-hr Bubbler, Sodium Arsenite, Frit or Orifice Method. Data from EPA, Region V (1975--unpublished). Format and abbreviations are described in Figure 48.

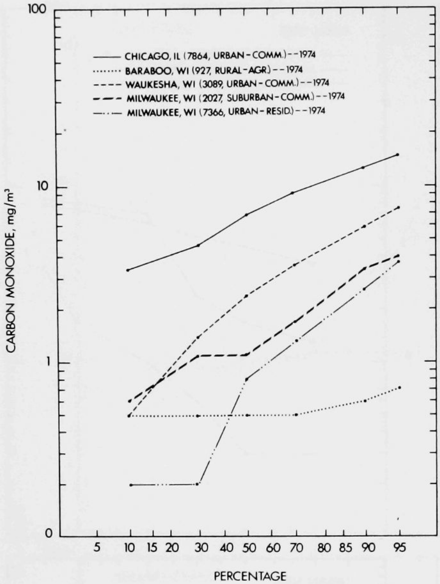
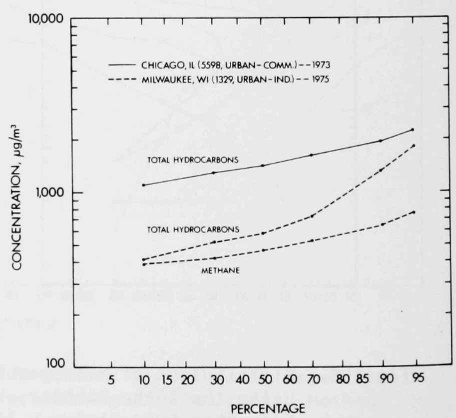


Fig. 51.

Distribution of Carbon Monoxide Concentrations at Selected Sites Using the 1-hr, Non-Dispersive Infrared Method. Data from EPA, Region V (1975--unpublished). Format and abbreviations are described in Figure 48.

Fig. 52.

Distribution of Hydrocarbon Concentrations at Selected Sites Using the 1-hr, Flame Ionization Method. Data from EPA, Region V (1975--unpublished). Format and abbreviations are described in Figure 48.



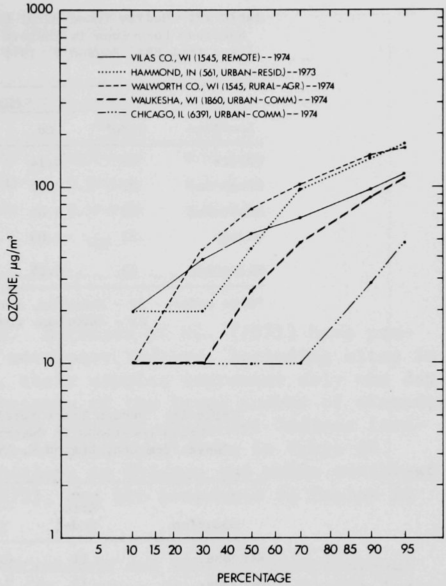


Fig. 53.

Distribution of Ozone Concentrations at Selected Sites Using the 1-hr, Instrumental Chemiluminescence Method. Data from EPA, Region V (1975--unpublished). Format and abbreviations are described in Figure 48.

Trace metal measurements in the Lake Michigan region are generally scattered and infrequent. Of the states surrounding the Lake, only Wisconsin has measured trace metal concentrations at more than a few locations. The Wisconsin measurements include Cu, Fe, Pb, and Mn, and cover the years 1973 and 1974. Still, relatively few samples per year were generally analyzed, *e.g.* the data for 1974 represent less than 10 samples per site.

The Wisconsin data have been grouped according to the character of the sampling location. Tables 16, 17, and 18 present 1974 medians for rural, suburban, and urban sites, respectively, in eastern Wisconsin. These data are

Table 16. Median Trace Metal Concentrations at Selected Rural Locations in Eastern Wisconsin during 1974 (Data from EPA, Region V, 1975--personal communication)

Location	*Site Code**	*Concentration, μg/m³* Cu	Fe	Pb	Mn
Franklin	31	0.04	0.30	0.20	0.02
Wind Lake	31	0.02	0.20	0.10	0.02
Husher	32	0.50	0.50	0.10	0.02
Union Grove	32	0.01	0.20	0.10	0.02
Burlington	33	0.09	0.60	0.30	0.02
Vilas Co.	41	0.07	0.20	0.001	0.01

**Sites codes: 31 Rural, near urban*
32 Rural, agricultural
33 Rural, commercial
41 Remote

Table 17. Median Trace Metal Concentrations at Selected Suburban Locations in Eastern Wisconsin during 1974 (Data from EPA, Region V, 1975--personal communication)

Location	*Site Code**	*Concentration, μg/m³*			
		Cu	*Fe*	*Pb*	*Mn*
DePere	22	0.14	0.14	0.10	0.02
Green Bay	22	0.02	0.80	0.20	0.02
Manitowoc	22	0.05	0.30	0.10	0.01
Wausau	22	1.05	0.40	0.40	0.01
Milwaukee	23	0.05	0.80	0.40	0.03

**Site codes: 22 - Suburban, residential*
23 - Suburban, commercial

Table 18. Median Trace Metal Concentrations at Selected Urban Locations in Eastern Wisconsin during 1974 (Data from EPA, Region V, 1975--personal communication)

Location	*Site Code**	*Concentration, μg/m³*			
		Cu	*Fe*	*Pb*	*Mn*
Kenosha	11	0.03	0.30	0.10	0.01
Menasha	11	0.16	1.90	0.30	0.03
Racine	11	0.02	2.70	0.20	0.05
Milwaukee	12	0.15	0.60	0.40	0.03
Walworth Co.	12	0.20	0.20	0.10	0.01
Appleton	13	0.02	0.50	0.20	0.02
Fond du Lac	13	0.07	0.30	0.10	0.01
Milwaukee	13	0.13	1.30	0.50	0.06
Neenah	13	0.04	0.41	0.10	0.01
Port Washington	13	0.01	0.30	0.10	0.01
Racine	13	0.15	1.10	0.50	0.04
Stevens Point	13	0.01	0.10	0.10	0.02
Waukesha	13	0.03	0.33	0.30	0.02
Whitewater	13	0.17	0.30	0.20	0.02

Site codes: 11 - Urban, industrial
12 - Urban, residential
13 - Urban, commercial

summarized in Table 19, which shows concentrations generally increasing with urbanization for Fe, Pb, and Mn, but not Cu. The tables show that median concentrations of all metals, especially Cu, vary considerably between sites of the same category. The overall variability is also expressed as the maximum/minimum ratio in Table 19. Cu and Pb, with ratios of 105 and 500, respectively, are primarily generated as aerosols by industrial and fuel combustion, whereas Fe (13) and Mn (6) have primarily natural sources, such as soil dust.

Samples from rural locations in other states of the Lake Michigan region are very limited. Dams *et al.* (1970) presented data on 33 elements in a

Table 19. Summary of Median Trace Metal Values in Eastern Wisconsin during 1974 (Data from EPA, Region V, 1975--personal communication)

Site Category	Concentration, $\mu g/m^3$			
	Cu	*Fe*	*Pb*	*Mn*
Rural	0.01-0.50	0.20-0.60	0.001-0.30	0.01-0.02
Suburban	0.02-1.05	0.14-0.80	0.10-0.40	0.01-0.03
Urban	0.01-0.20	0.10-2.70	0.10-0.50	0.01-0.06
Max/min ratio	105	13	500	6

single sample from rural Niles, Michigan. Harrison *et al.* (1971) have presented similar data for 25 locations in northwest Indiana, including sites in rural or suburban areas. Unfortunately, their samples represent only one day. Nevertheless, the data are of interest because of the large number of elements included. The range of values at the eight suburban northwest Indiana locations and the data from the single sample at Niles are shown in Table 20. Available data on trace element concentrations in Chicago and urban northwest Indiana have been summarized by Gatz (1975), and are presented in Tables 21 and 22, respectively.

Comparison of urban and rural concentrations and spatial distributions led Harrison *et al.* (1971) to identify: (*i*) a group of elements having large local sources (Cu, W, Cr, Zn, Sb, Ga, Br, Ag, Fe, and Ce), (*ii*) a group of elements not likely to have local pollution sources (Sm, Eu, Sc, Na, K, Al, and Ti), and (*iii*) an intermediate group of elements probably having weak local sources (Th, La, Mn, Hg, As, S, Co, Se, Mg, Ca, and V).

Pollutant concentrations over Lake Michigan are virtually unmeasured, but would be expected to depend strongly on wind direction and season of the year. Gillette (1970) measured Pb concentrations of 0.01-0.6 $\mu g/m^3$ over the Lake when upwind of the industrial southwest shore, and 0.2-1.4 $\mu g/m^3$ when downwind. Hesse (1973) measured a mean Pb concentration of 0.03 $\mu g/m^3$ along the eastern shore of Lake Michigan.

SUMMARY

Within the framework of national emissions of TSP, SO_2, and NO_x, emission rates for these pollutants are generally moderate in the Lake Michigan region, except for an area of very high rates along the southwest shore of the Lake.

Concentrations of the major pollutants generally increase with population density and industrialization. However, the opposite is true for ozone, where highest concentrations occur in rural areas. Trace element measurements are relatively few and scattered. Concentrations of most pollutant metals generally increase from rural to industrial locations, but there is considerable variability owing to the influence of local sources. Pollutant measurements over Lake Michigan are rare.

Table 20. Trace Element Concentrations ($\mu g/m^3$) in Suburban and Rural Areas at the Southern End of Lake Michigan

	*Suburban Northwest Indiana**					
Element	*Maximum*		*Minimum*		*Rural Niles, Michigan†*	
S	18,000	±10,000	3,000	±3,000	11,000	±5,000
Fe	5,375	± 200	1,420	± 120	1,900	± 100
Ca	4,330	± 400	1,410	± 200	1,100	± 200
Cu	860	± 60	26	± 5	280	± 20
Al	3,100	± 300	1,650	± 150	1,200	± 70
Mg	1,350	± 600	530	± 300	500	± 300
K	1,810	± 110	730	± 90	720	± 50
Zn	315	± 20	115	± 20	160	± 20
Na	405	± 30	225	± 50	170	± 20
Mn	160	± 20	63	± 3	62	± 3
Br	75	± 7	26	± 3	38	± 6
Ti	265	± 80	120	± 25	120	± 25
Cr	18.2	± 0.8	6.2	± 0.8	9.5	± 0.8
Sb	11.5	± 1.0	2.2	± 0.3	6.0	± 0.3
V	17.3	± 0.8	4.5	± 0.4	5.0	± 0.3
Ce	7.0	± 0.6	1.4	± 0.1	0.82	± 0.06
As	8	± 4	2.7	± 2	4.6	± 2.0
La	4.4	± 0.4	0.9	± 0.1	1.3	± 0.3
W	1.3	± 0.7	0.3	± 0.3	0.4	± 0.2
Hg	4.8	± 1.4	0.8	± 0.4	1.8	± 0.3
Se	4.4	± 1.2	1.1	± 0.4	2.5	± 0.5
Ga	3.5	± 1.0	0.5	± 0.3	0.9	± 0.4
Sc	2.55	± 0.15	0.95	± 0.1	1.2	± 0.1
Co	1.6	± 0.15	0.55	± 0.06	0.95	± 0.1
Th	0.68	± 0.07	0.22	± 0.04	0.27	± 0.08
Sm	0.65	± 0.20	0.17	± 0.02	0.24	± 0.03
Eu	0.17	± 0.03	0.06	± 0.01	0.055	± 0.02
In	0.09	± 0.06	0.04	± 0.03	0.04	± 0.03

**Data represent samples from a single day.*

†Data represent a single sample.

References: Northwest Indiana--Harrison et al. (1971); Niles, Michigan--Dams et al. (1970).

Table 21. Trace Element Concentrations ($\mu g/m^3$) in Chicago Aerosols (Modified from Gatz, 1975)

	Source of Data and Period of Sampling							
	Harrison and Winchester	*Brar et al.*	*National Air Surveillance Network*				*Chicago Air Sampling Network*	
Element	*1968*	*1968*	*1966*	*1967*	*1968*	*1969*	*1970-1971*	*Composite Model**
Al		1.5						(1.5)
As							0.017[a]	0.02
Cd	0.015		0.03	0.01	0.008	0.015		0.01
Cr		0.018	0.008	0.005	0.023	0.016		0.02
Cu	0.182		0.08	0.09	0.13	0.12	0.14	0.14
Fe		2.6	2.4	2.7	4.3	4.0	3.3	3.5
Mn		0.45	0.08	0.08	0.09	0.12	0.10	0.10
Ni			0.029	0.031	0.033	0.051		0.04
Pb	2.5		1.6	1.2	1.6	1.6	1.2	1.2
Ti			0.01	0.02		0.02		(0.2)[b]
V		0.024	0.048	0.059		0.096		0.08
Zn		0.062	1.7	1.1			0.65	(0.3)[b]

**Parentheses indicate considerable uncertainty in model concentrations due to limited number of measurements.*

[a]Arsenic measured September to December, 1971, only.

[b]Estimated from St. Louis data of Gatz (1974). National Air Surveillance Network data for these elements are not reliable (Winchester, 1975--personal communication; Akland, 1975--personal communication).

References: Harrison and Winchester (1971); Brar et al. (1970); National Air Surveillance Network--EPA (1972, 1973a); Chicago Air Sampling Network--Chicago Dep. Air Pollut. Control, 1971).

Table 22. Trace Element Concentrations ($\mu g/m^3$) in Northwest Indiana Aerosols (Modified from Gatz, 1975)

	Source of Data and Period of Sampling										
	Harrison and Winchester	*Harrison et al.*	*National Air Surveillance Network*								
			Hammond				*East Chicago*				
Element	*1968*	*1969*	*1966*	*1967*	*1968*	*1969*	*1966*	*1967*	*1968*	*1969*	*Composite Model**
Al		1.96									(2.0)
As		0.005									(0.005)
Cd	0.014		0.00	0.01		0.011	0.01	0.01	0.007	0.028	0.02
Cr		0.043	0.002	0.010		0.019	0.014	0.018	0.037	0.064	0.04
Cu	2.2	0.80	0.07	0.18		0.11	0.15	0.18	0.31	0.27	0.2
Fe		5.83	2.4	3.7	4.6	5.5	4.0	4.3	8.1	9.9	6.0
Mn		0.175	0.09	0.16	0.13	0.24	0.12	0.15	0.19	0.35	0.3
Ni		<0.019	0.014	0.026	0.020	0.029	0.036	0.035	0.056	0.104	0.06
Pb	1.8		0.8	1.2	0.93	1.2	1.0	1.2	1.1	2.6	1.5
Ti		0.185	0.00	0.02		0.05	0.02	0.02		0.10	(0.2)[a]
V		0.0084	0.017	0.034		0.048	0.042	0.050		0.115	0.08
Zn		0.44	0.5	0.7			1.5	1.0			(0.4)[a]

**Parentheses indicate considerable uncertainty in model concentrations due to limited number of measurements.*

[a]Estimated from Harrison et al. (1971) only. National Air Surveillance Network data for these elements are not reliable (Winchester, 1975--personal communication; Akland, 1975--personal communication).

References: Harrison and Winchester (1971); Harrison et al. (1971); National Air Surveillance Network--EPA, 1972, 1973a).

METEOROLOGICAL INFLUENCES ON AIR POLLUTANT CONCENTRATIONS

Air pollutants may be viewed as having a life cycle in the atmosphere. This cycle begins with their emission or injection into the atmosphere at their source. The cycle continues with the transport and diffusion (dispersal) of the pollutants by air motions, and their possible transformation into secondary pollutants. It ends with the deposition of the pollutant at or near the earth's surface.

Meteorological processes have little direct effect upon the quantity of emissions of man-made pollutants, although they may have indirect effects; *e.g.* high temperatures in summer indirectly cause more power plant emissions by creating a demand for power to run air conditioners. Meteorological processes have a more direct influence on emissions of natural pollutants. For example, the amount of soil dust blown into the atmosphere depends upon wind conditions and soil moisture conditions, among others.

Meteorological processes have their greatest effect on pollutant concentrations during the transport phase of the life cycle. It is here that high winds and extreme turbulence through a deep layer of the atmosphere can dilute pollutants with clean air and reduce their concentrations to less than detectable, and it is here that the absence of air motions or unfavorable air motions can bring pollutants to our noses or our farm crops with little or no dilution. These processes are discussed in this section under two general headings. The first of these covers meteorological processes as they affect concentrations over land, away from lake influences; the second covers conditions over the Lake and lake-affected onshore areas.

Deposition processes also deplete airborne pollutants, of course. Deposition depends, in some cases, on characteristics of the pollutant and the deposition surface as well as on meteorological conditions. Meteorological processes of pollutant removal from the atmosphere are treated in a later section.

INFLUENCES OVER LAND

Weather affects pollutant concentrations primarily through air motion (wind) or lack of it. Wind is usually thought of in terms of horizontal motion, but vertical (up-and-down) motions and the depth of the layer mixed by these motions influence pollutant concentrations very directly. Large-scale weather conditions known as stagnations (slow-moving high-pressure systems) are characterized by a combination of low wind speed and very limited vertical mixing. Furthermore, they can last for days, leading to very serious buildups of pollutant concentrations.

In this section we describe the basic physical properties and the time- and space-variability of the following weather influences on pollutant concentrations: wind, vertical mixing, and stagnations.

Wind

For someone who lives near a large pollutant source, wind direction is the crucial factor that determines whether the smoke plume comes his way or not. One living east of a source welcomes an east wind (*i.e.* out of the east) because that means the smoke or odor will be carried away from him, towards the west. Over a long period of time, the distribution of wind direction will have a large influence on the distribution of pollutant concentrations around a single source.

Wind speed is another important influence on concentration. Consider, for example, a smokestack emitting 10 kg of particulate matter per second. In a 1 m/sec wind, 10 kg will be contained in 1 m of plume length. For a 10 m/sec wind, the same 10 kg will be contained in 10 m of plume length. For equal plume cross-sectional areas, the concentration in the first case would be 10 times that of the higher wind speed. Thus, concentration is inversely proportional to wind speed.

When most of us think about wind, we only consider the direction and speed that we sense while walking about, *i.e.* at ground level. However, neither speed nor direction usually remains constant with height in the lower atmosphere. Friction of the air on ground-based surfaces usually causes wind speeds to increase with height and wind directions to turn more and more to the right (in the Northern Hemisphere) with altitude. For example, a small helium-filled balloon might be carried slowly northward when first released near the ground, but as it rises it would likely pick up speed and move more and more to the east, and later even southeast or south. Such directional turning occurs mostly within about 1000 m (∿3300 ft) of the surface. The variation of speed and direction with height is an important feature of weather effects on pollutant concentrations when one considers that the large polluters, such as power plants, may have smokestacks high enough to release pollutants at 200-300 m (∿700-1000 ft) or more above ground.

Wind speed and direction near the ground* are measured and recorded continuously at weather stations. Values representing averages over one minute are transmitted at hourly or 3-hourly intervals for operational meteorological purposes. Thus, hourly or 3-hourly surface-wind data are available for many locations in the Lake Michigan region. Observations of winds aloft require pilot balloon or rawinsonde observations. These are available less frequently and at far fewer locations. Regional surface-wind speed and direction were summarized earlier in this volume. Upper wind climatic averages are available in the literature (Crutcher and Halligan, 1967).

Until now we have been discussing winds that represent observations of a few minutes to an hour or so. However, if one watches the motion of a well-made wind vane that is free to rotate about a vertical axis, it becomes obvious that there are many very rapid fluctuations in wind direction. If one were to watch a bi-directional wind vane (or bivane) whose tail can go up and down as well as side to side, short-period up and down fluctuations would also be evident. Similar fluctuations in wind speed also occur. These variations of instantaneous wind speeds and directions about long-term (one hour, say) mean values are turbulent fluctuations, and are responsible for mixing of pollutants into ever-greater volumes of the atmosphere.

It is important to note that there are different scales of turbulent fluctuations, or different-sized eddies. An eddy may be viewed as a lump of some fluid which has broken away from the mean flow and is leading an

**10 m (33 ft) above ground level is the standard height.*

independent life of its own for a short time, before being absorbed again into the mean flow at another location (Sutton, 1953). Eddies that are large compared to the diameter of a smoke plume act to displace large segments of the plume up or down, or horizontally. Small eddies (relative to plume diameter) act to tear the plume into small bits, thus diluting and mixing it with clean air and reducing pollutant concentrations.

Any attempt to calculate the concentration of pollutants downwind of a source must take into account the magnitude of these turbulent fluctuations. Hay and Pasquill (1957) conducted experiments which showed that the vertical distribution of particle concentration downwind of an elevated source was related to the standard deviation of the wind elevation angle above the horizontal, as measured with a bivane.

Many methods currently used for estimating diffusion of pollutants assume Gaussian (*i.e.* normal) distributions of pollutant concentration both in the horizontal cross-wind and vertical directions. These distributions are specified in terms of σ_y (sigma-y) and σ_z (sigma-z), the respective standard deviations of pollutant distribution across the plume in the horizontal and vertical. Turner (1969) has discussed practical methods of atmospheric dispersion estimation.

Many investigators have attempted to relate measured distributions of pollution-simulating tracer materials to observed horizontal and vertical wind fluctuations under widely varying atmospheric conditions. For an extensive discussion of these experiments, see Islitzer and Slade (1968).

Wind fluctuations are not routinely measured by the National Weather Service as are wind speeds and directions. Thus, it is not possible to show how mean values of diffusion parameters vary over the Lake Michigan region or to show how they vary with height or atmospheric stability, even over land areas. At present, a separate investigation of diffusion parameters is usually required for each new site of practical interest, such as a power plant.

To permit diffusion estimations in the absence of detailed wind observations, Pasquill (1961) proposed a method for expressing the vertical and horizontal spread of a diffusing plume in terms of more commonly observed weather parameters. This method was modified by Gifford (1961) to express diffusion in terms of σ_y and σ_z. The Pasquill-Gifford method was used by Turner (1969) in his discussion of practical methods of estimating diffusion. Because of its relative simplicity, the Pasquill-Gifford method has sometimes been used in meteorological situations, or at heights or downwind distances, for which it was never intended. Users should take care that they understand the intended uses and limitations of this method in all applications.

Vertical Mixing

The depth through which the lower atmosphere is well-mixed is a primary influence on pollutant concentrations. For a constant wind speed, the atmospheric volume available for dilution of pollutants will be proportional to the depth of mixing. The concentration of pollutants in the mixed layer is thus inversely proportional to the mixing depth.* Consequently, the deeper the

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**Also referred to in this report as mixing height.*

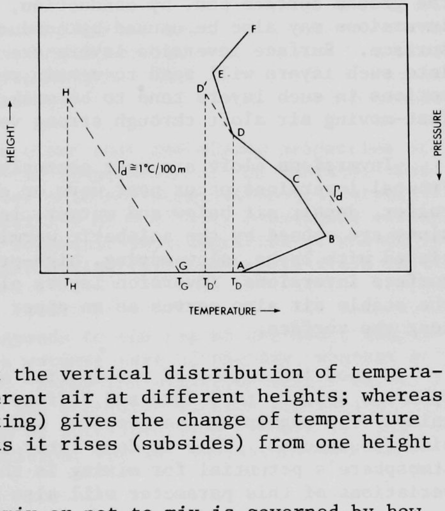
mixed layer, the lower the concentration of pollutants, if emissions and wind speed remain constant. The depth of the surface mixed layer varies markedly with hour of the day and with season of the year. It can also vary strongly from place to place within the region, depending on the nature of the underlying surface. To understand why these large variations occur, we will consider some of the basic physics of the mixing process.

Strong mixing implies vigorous up and down motions in the atmosphere (the result of an unstable condition). The absence of mixing implies very limited up and down motions (a stable condition). Whether the atmosphere is stable or unstable at a given time depends on the way the air temperature varies with height above the ground (vertical distribution of temperature).

The vertical distribution of temperature is usually measured by an instrument carried aloft by a balloon that radios back, to a receiver on the ground, temperature and pressure measurements at frequent intervals as the balloon rises. Temperature is plotted against pressure, or height, as line ABCDEF in Figure 54. The dry adiabatic rate of cooling, Γ_d--the dashed line GH (or dry adiabat)--is the rate at which a parcel of dry air cools as it rises in the atmosphere if there is no heat exchange with its surroundings. Thus, if a parcel of air with a temperature T_G were lifted from the surface to point H, it would cool to T_H. This rate of cooling can be applied to any parcel of air at any height. For example, if a parcel of air at D with temperature T_D were raised to point D´, its temperature would drop to $T_{D}´$. Conversely, if air at D´ subsided to D, its temperature would increase from $T_{D}´$ to T_D.

Fig. 54.

Illustration of Dry Adiabatic Rate of Cooling, Γ_d, and Vertical Distribution of Temperature, ABCDEF. (See text for further discussion.)



It is important to understand that the vertical distribution of temperature indicates the temperature of different air at different heights; whereas, the dry adiabatic rate of cooling (heating) gives the change of temperature per unit height within one air parcel as it rises (subsides) from one height to another.

The tendency of the atmosphere to mix or not to mix is governed by how the vertical distribution of temperature compares to Γ_d. We can identify the following possible situations (all illustrated in Fig. 54):

1. If the actual decrease of temperature with height in a layer is more rapid than Γ_d, that layer is unstable. Thus, layer CD is unstable. This is clear if we recall that a parcel lifted from point C will cool at rate Γ_d, so that upon reaching the height of point D, the parcel will have a temperature warmer than its environment (T_D) and hence be less dense and tend to keep on rising (an unstable condition). Conversely, a parcel displaced downward from point D will warm at a rate Γ_d, so that when it reaches the level of point C it will be cooler than its environment, and hence denser, and will tend to keep on sinking (again an unstable condition).

2. If the actual decrease of temperature with height in a layer is equal to Γ_d, the layer is said to be neutral. Layer BC is an example.

3. If temperature decreases with height, but more slowly than Γ_d, the layer may be relatively stable or unstable, depending on its moisture conditions. Such a layer is DE.

4. If temperature increases with height, it is called an inversion because it is the inverse of the normal condition (temperature decreasing with height). Layer AB is an example of this very stable condition.

Inversions may occur at the surface (AB) or aloft (EF). Surface inversions occur frequently on clear nights when strong radiation heat losses cool the ground surface and, by conduction, the overlying air layer. Surface inversions may also be caused by conduction in warm air moving over a colder surface. Surface inversion layers are very stable, and pollutants emitted into such layers will tend to remain relatively undiluted. Further, air motions in such layers tend to be weak, because they are not coupled to the fast-moving air aloft through strong vertical mixing.

Inversions aloft are most commonly frontal or subsidence inversions. Frontal inversions occur near warm or cold fronts at the interface between colder, denser air below and warmer, less dense air above. Subsidence inversions are caused by the adiabatic warming of sinking air and are often associated with large, slow-moving, high-pressure systems. As in the case of surface inversions, inversion layers aloft are stable. In the latter case, the stable air also serves as an upper limit to the depth of the mixed layer near the surface.

A good indication of the spatial and temporal variation of the atmosphere's ability to dilute and diffuse pollutants emitted into it can be gained from examining the temporal and spatial variability of low-level inversion frequencies. This is done later in this section. Another measure of the atmosphere's potential for mixing is the mixing depth. Spatial and temporal variations of this parameter will also be examined.

The observed mixing height is determined from a plotted temperature sounding and applies to the time of the sounding. It is the height above ground where the observed temperature decrease with height first becomes less rapid than the moist adiabatic rate of cooling.*

The afternoon maximum mixing height ordinarily is estimated, using an earlier temperature sounding and the observed maximum surface temperature. It is defined as the height at which a dry adiabat through the afternoon maximum surface temperature intersects the earlier temperature sounding. Both kinds of mixing heights are illustrated in Figure 55.

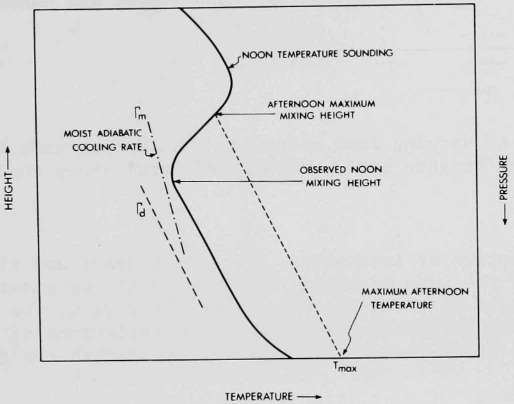


Fig. 55. Illustration of Observed Noon Mixing Height and Afternoon Maximum Mixing Height. (See text for details.)

From the previous discussion, it is clear that the mixing properties of the lower atmosphere depend strongly on the temperature of the surface. Surface inversions form and limit mixing over cold surfaces, while deep mixing occurs over hot surfaces. Thus, the stability of the lower atmosphere varies markedly with the sun's daily cycle. A schematic representation of the daily cycle of stability in the lower atmosphere during fair weather is given in Figure 56.

The afternoon maximum height corresponds to the top of the deep, highly turbulent mixed layer present during the warmest part of the day, whereas a low-level stable layer appears at night. Above the nighttime stable layer, a mixed layer of low turbulence appears. The schematic diagram provides a unifying preview of the daily variations of both inversion frequencies and mixing heights, discussed below. In addition, spatial variations over land

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**The rate of cooling experienced by a parcel of air saturated with moisture. Such cooling is less rapid than in the corresponding dry process because saturated air condenses liquid water upon further cooling, releasing the latent heat of condensation. The moist adiabatic cooling rate becomes rapid with height, approaching Γ_d at high altitudes. In contrast, Γ_d is constant with height.*

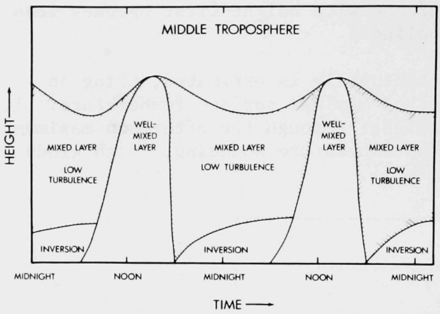


Fig. 56.

Schematic Diagram of Daily Mixing Cycle in the Lower Atmosphere during Fair Weather. Based on figures of Munn (1976) and Randerson (1975).

occur in response to varying land usage, so that differences in inversion frequencies and mixing heights between urban and rural areas should be apparent.

Inversions

In our examination of inversions, we present space and time variations over land areas of the Lake Michigan region and begin by examining the variation of time-averaged rural conditions across the region. We shall then narrow the scope and examine some detailed time variations at a single rural site. Finally, we shall look at how urban areas disturb the general rural pattern.

Rural Conditions

Hosler (1961) examined vertical temperature variations measured at radiosonde sites across the United States. His paper gives the percent of time when inversions and constant-temperature layers based below 150 m (500 ft) occur, for individual seasons, as well as for the whole year. Data for four locations in, or near, the Lake Michigan Basin are given in Table 23.

The values of total time provide a general picture of regional inversion frequency behavior. There were relatively small differences between seasons at all four sites. The greatest seasonal difference was 9% between spring and fall at Joliet. There was even less spatial variation in a given season; 7% in both winter and summer were the largest variations. Thus, Hosler's work shows that inversions or isothermal layers were present below 150 m between about 30 and 35% of the time in all seasons of his study period over all the rural land areas of the Lake Michigan region. Holzworth's (1974--unpublished) more extensive study of low-level stability in the U. S. is in substantial agreement with these results.

Although variations in total time frequencies were small, there were large variations in frequency over the course of a day (Table 23). At all sites, frequencies were large at 0600 hr, but they dropped rapidly to low daytime values, and rose sharply again near sundown. The maximum values (above 80%) occurred during the evening. The daily variation was largest in spring and summer, but occurred at all sites in all seasons. The day-night differences appear to have been smaller at Sault Ste. Marie in all seasons. This is possibly an effect of the proximity of Lake Superior. Lake effects will be examined in greater detail later.

Table 23. Percent Frequency of Inversions or Isothermal Layers Based below 150 m (500 ft) above Ground in the Lake Michigan Region (Data from Hosler, 1961)

		Frequency, %				
		Central Standard Time				Total
Location	*Season*	*0600*	*0900*	*1800*	*2100*	*Time*
Flint/Mt. Clemens, Michigan	Winter	46	15	28	25	29
	Spring	65	9	4	49	30
	Summer	70	5	2	72	27
	Fall	36	10	21	47	34
Green Bay, Wisconsin	Winter	53	31	29	54	34
	Spring	71	8	9	58	33
	Summer	76	9	4	76	29
	Fall	61	16	22	59	33
Joliet/Peoria, Illinois	Winter	56	25	29	46	33
	Spring	63	5	3	63	29
	Summer	65	7	4	82	34
	Fall	73	15	39	71	38
Sault Ste. Marie, Michigan	Winter	58	53	35	48	36
	Spring	60	29	14	63	29
	Summer	73	12	12	84	32
	Fall	66	25	38	55	36

Early morning and late evening inversion frequencies are largest from spring through fall. This reflects the greater frequency of conditions favorable for inversions, such as clear skies and light winds, during these seasons.

Hosler (1961) measured vertical temperature variations by radiosonde, but such data may also be collected on towers. There are basic differences between measuring inversions on towers and by radiosonde. Both methods have advantages and disadvantages. The advantage of the tower is that it can provide measurements continuously in time, but only at a few fixed heights. The radiosonde, on the other hand, can provide nearly continuous measurements vertically, but only at a few fixed times during the day. Thus, the radiosonde may detect thin inversion layers between the heights of the tower sensors. The tower can provide a better indication of the daily frequency of occurrence of inversions, but only between fixed heights.

Time variations of rural low-level inversion frequency are seen in greater detail from the hourly temperature data collected at several heights on the 46 m (~150 ft) tower at Argonne National Laboratory (ANL) (Fig. 57). In comparing the Argonne data with others, it must be understood that the ANL measurements were made only between 1.7 and 44 m (5.5 and 144 ft) above the ground. This is a considerably shallower layer than that covered by Hosler [150 m (500 ft)] or by urban tower measurements to be presented later.

The daily variation of percent frequency of occurrence of inversions between 1.7 and 44 m at ANL is shown in Figure 57 for January, April, July, and October (Moses and Bogner, 1967). The data are averages for 15 years, 1950 through 1964. During all of the months shown, average frequencies stayed relatively constant during the night hours and midday hours, respectively, with sharp changes at sunrise and sunset. Nighttime frequencies were lowest in January (47%), but increased in April (72%) and July (90%) and decreased slightly in October (82%). Midday average frequencies were less than 5% in

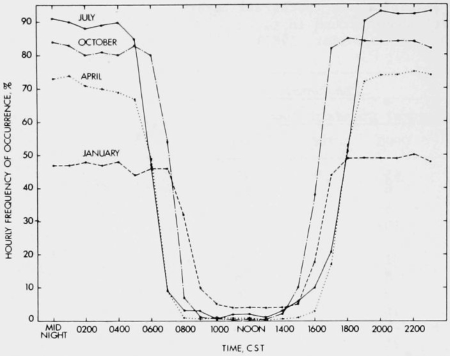


Fig. 57.

Chance of Inversion between 1.7 and 44 m above Ground at Argonne National Laboratory by Hour of Day for January, April, July, and October. Data from Moses and Bogner (1967).

all seasons. Moses and Bogner (1967) may be consulted for additional data on inversion frequencies, and for frequencies of joint occurrences of selected vertical temperature differences with other meteorological parameters.

Wind direction frequency during inversions is one of the more important of these joint occurrences for air pollution. Figure 58 shows wind direction frequencies for two conditions: (*i*) 44 m (144 ft) temperature >1.7 m (5.5 ft) temperature, and (*ii*) 44 m temperature ≤1.7 m temperature. Again, these data represent average frequencies at ANL for 1950-1964. The solid line represents the more stable condition (*i*), and the dashed line the less stable condition (*ii*). The shaded area emphasizes those directions where frequencies are higher during low-level surface inversions.

Both stability conditions occur with all wind directions, but given an inversion, the distributions in all seasons are somewhat different than given no inversion. Larger frequencies are found for south-southwest directions during inversions in all seasons. In April, July, and October, east-south directions are also more likely during inversions than under less stable conditions. Winds from west-north-east are somewhat more likely under non-inversion conditions.

Urban Effects

Vertical temperature measurements have been made in Chicago, the largest city in the Lake Michigan region, since 1969. Unfortunately, inversion frequencies in the lowest 150 m (500 ft) have not been compared with Hosler's (1961) data for rural sites. Urban effects on stability can be shown in terms of differences between urban and rural mixing heights. These data are compared later in this volume.

Information on the vertical distribution of temperature in urban locations is available from measurements made on tall towers and from helicopters. Tower observations were made in Louisville, Kentucky (DeMarrais, 1961) and Minneapolis, Minnesota (Baker *et al.*, 1969).

In Louisville, observations were reported for September 1957 to June 1958 for nighttime hours. Inversions occurred about 9% of the time between 18 m and 52 m (60 and 170 ft) and about 18% of the time between 52 m and 160 m (170 and 520 ft).

In Minneapolis, the observations covered all hours between June 1961 and July 1968. Sensors were at 21, 52, and 152 m (70, 170, and 500 ft). The data were summarized in terms of the number of inversions per 100 days, rather than percent time of inversion conditions, and thus are not directly comparable to the Louisville data.

Still a comparison of relative frequencies in two layers may be made for Louisville and Minneapolis, since the sensor heights were nearly the same. In Louisville, inversions occurred in the upper layer about twice as often as in the lower layer. In Minneapolis, the upper layer had inversions ten times as often as the lower layer. Baker *et al.* (1969) interpreted this difference as an indication of greater urban heating of the 21-52 m layer in Minneapolis.

In addition, Baker *et al.* presented average annual inversion intensity and frequency for the years 1961-1968. Both parameters appeared to decrease during the period, suggesting that the increase in urbanization and industrialization during the period was warming and destabilizing the urban atmosphere.

Helicopter measurements have been reported for New York City (Bornstein, 1968) and for Cincinnati (Clarke, 1969). Although they cannot provide continuous observations, helicopters are useful observation platforms for intensive case studies of three-dimensional temperature variations over cities.

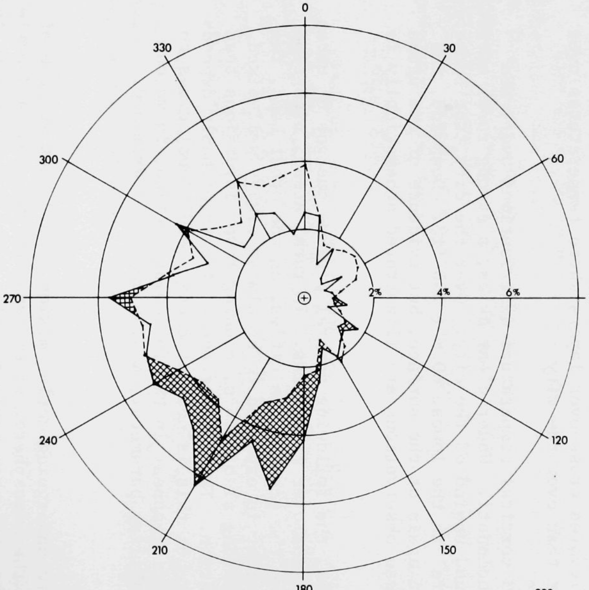
Bornstein (1968) measured urban and non-urban vertical temperature profiles on 42 occasions near sunrise time. He found urban inversions to be less intense and much less frequent than those in nearby rural areas. On the other hand, weak inversions were almost always present over the city at sunrise; their mean height was 310 m (∿1020 ft). On more than two-thirds of the flights, Bornstein found elevated cross-over layers where temperatures over the rural areas were higher than over the city.

Clarke (1969) measured vertical temperature distributions over, and upwind and downwind of, Cincinnati. Under clear skies, a strong rural surface inversion was typically found upwind of the city. Over the city, the temperature distribution was neutral in the lowest 60 m (∿200 ft). Downwind, the rural inversion was present again at the surface, but evidence of the urban plume was found aloft. These observations are illustrated schematically in Figure 59.

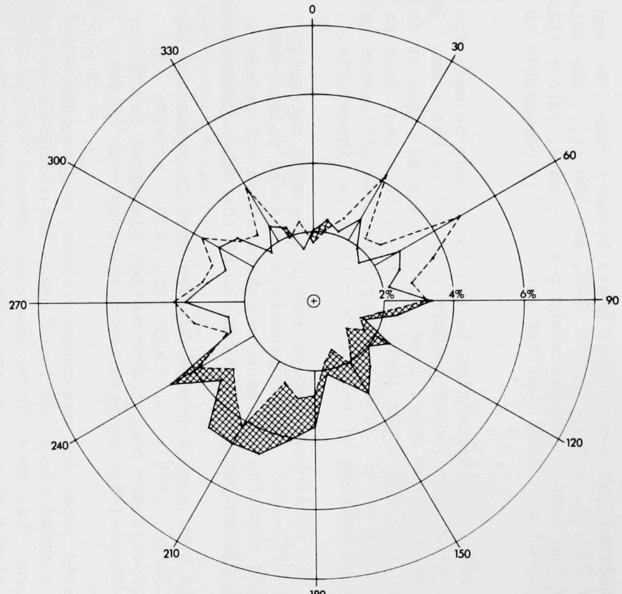
From these observations, the following general picture emerges of urban perturbation on rural inversion over land areas. In rural areas, nighttime inversions usually extend to the ground. In cities, on the other hand, the layer up to mean rooftop height is expected to be almost always well-mixed. At greater height, urban heating also occurs, causing fewer inversions than would occur in a rural location. The size of these effects probably depends on city size or population, but this is not yet clear. Additional clues to city effects on vertical mixing appear in the following section, in which another vertical mixing/stability parameter, mixing depth, is examined.

Mixing Depth

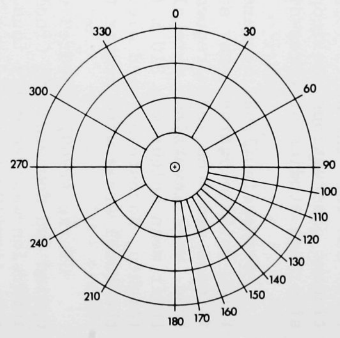
The depth of atmosphere undergoing active mixing is a direct measure of the dilution capability of the atmosphere, given constant emissions and horizontal wind conditions. The afternoon maximum mixing depth corresponds to the



a. January



b. April



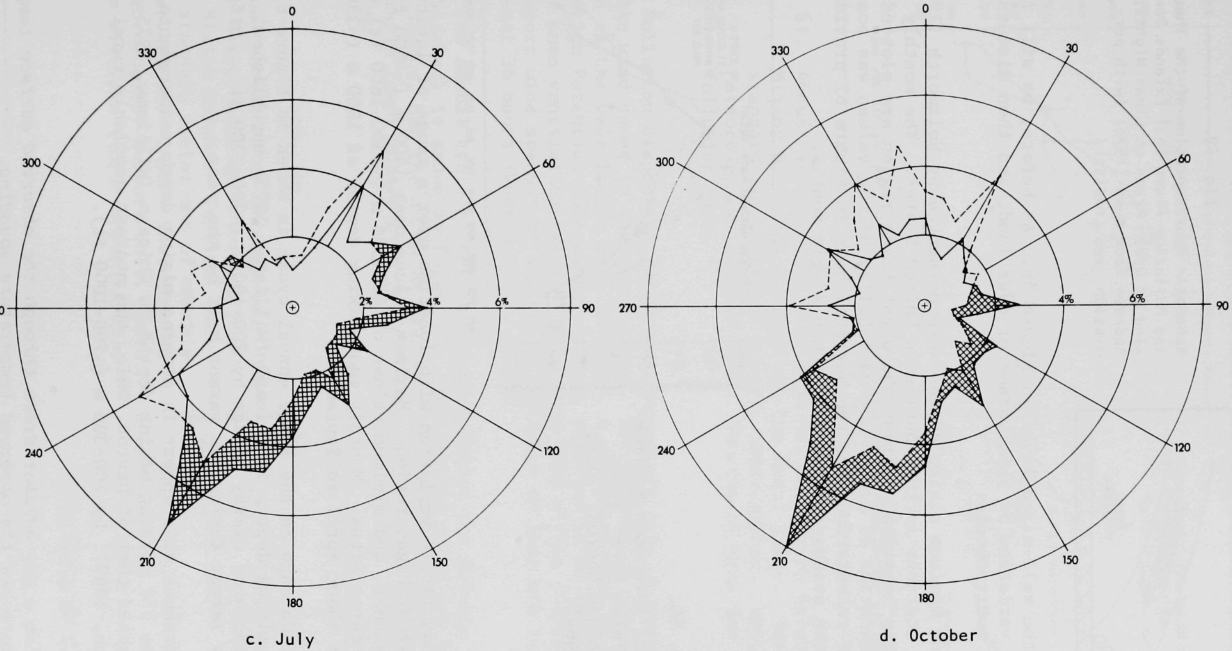


Fig. 58. Wind Direction Frequency Distribution for Inversions and No Inversions between 1.7 and 44 m above Ground at Argonne National Laboratory. Shaded areas indicate directions having higher frequencies of occurrence during inversions. Data from Moses and Bogner (1967).

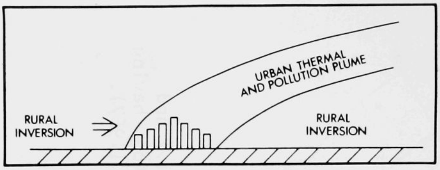


Fig. 59.

Schematic Representation of the Thermal and Pollution Plume That Extends Downwind of Urban Areas on Clear Nights. Redrawn from Munn (1976) (with permission, see credits).

maximum depth of the well-mixed layer in Figure 56. As before, we will first consider regional variation of this parameter over land, and then discuss its behavior in urban environments.

Mean afternoon maximum mixing depths were presented by Holzworth (1964) for 45 radiosonde stations in the contiguous United States. The monthly values for the three locations nearest the Great Lakes region are plotted in Figure 60. No indication of day-to-day variability of the values was possible from the method of calculation, but the vertical bars in Figure 61 provide an approximation of the standard deviation within single months.

Fig. 60.

Annual Variation of Afternoon Maximum Mixing Height at Three Rural Sites near the Lake Michigan Region. Data from Holzworth (1964).

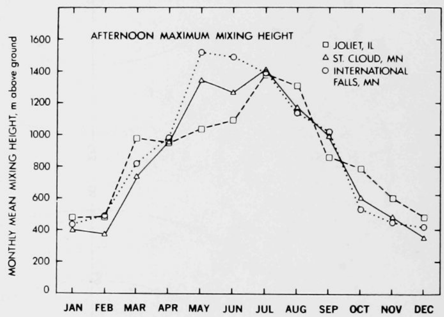


Figure 60 shows little variation with location over a range of latitudes that spans the Lake Michigan region. Maximum values near 1400 m (∿4600 ft) occur during the summer, and minimum values of 400-500 m (∿1300-1600 ft) occur in winter, at all three sites. Monthly mean mixing depths of 1000 m (∿3300 ft) or more occur from about April to September.

The effect of Chicago on the rural annual cycle is shown in Figure 61. Maximum afternoon mixing depths in Chicago (Williams, 1975--unpublished) generally exceed those of nearby Joliet by 200-400 m (∿700-1300 ft). Differences are slightly larger during the warmer half of the year.

Similar differences also appear in morning mixing depth measurements. Figure 61 shows the 5°C morning mixing depth* in Chicago (Williams, 1975--unpublished) to exceed that of Dayton, Ohio, the nearest available rural location (Holzworth, 1967), by 200-300 m (∿700-1000 ft).

**The height at which a dry adiabat drawn through the observed surface temperature plus 5°C intersects the observed temperature sounding.*

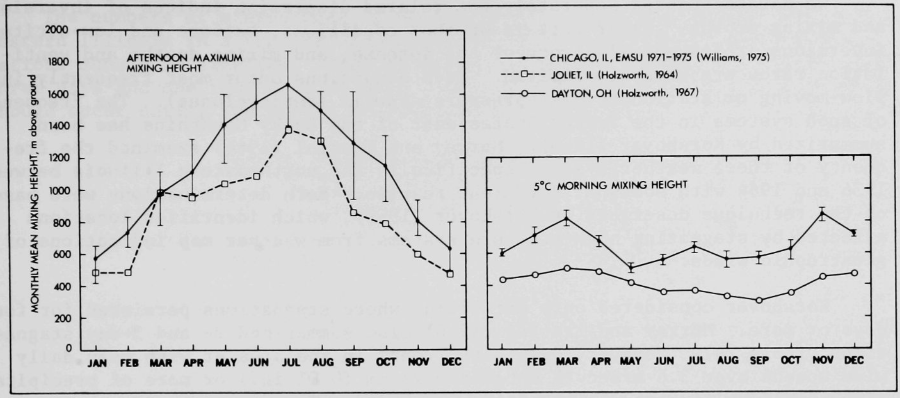


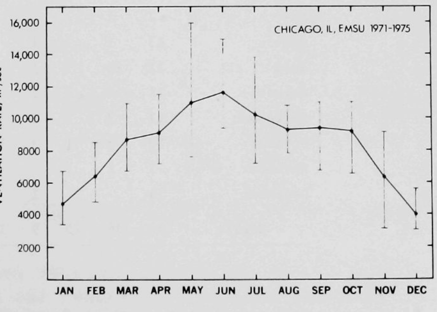
Fig. 61. Annual Variation of Afternoon Maximum Mixing Height and 5°C Morning Mixing Height at Chicago and Two Rural Sites. Vertical bars are standard deviations of monthly observations. EMSU = Environmental Meteorological Support Unit. Sources of data are in parentheses following site.

Pollution dispersion conditions depend not only on mixing depth, but also on mean wind speed in the mixed layer. The product of these two parameters is known as the ventilation rate (m^2/sec), a parameter used in making High Air Pollution Potential forecasts. Current practice is to call an Air Pollution Alert when ventilation rates of less than 6000 m^2/sec (~65,000 ft^2/sec) and transport wind speeds* of 4 m/sec (13 ft/sec) or less are forecast to last for at least 36 hours (Wuerch *et al.*, 1972).

The annual cycle of the ventilation factor for Chicago (Williams, 1975--unpublished) is shown in Figure 62. Ventilation rates are largest during the warm season, but the curve is flatter than for mixing height alone because generally lower summer wind speeds compensate to some extent for higher mixing depths.

Fig. 62.

Annual Variation of Chicago Ventilation Rate, Based on Afternoon Maximum Mixing Height. Vertical bars are standard deviations of monthly observations. EMSU = Environmental Meteorological Support Unit. Data from Williams (1975--unpublished).



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*The vector mean wind speed in the mixed layer.

We have discussed separately the related dispersion indices of inversions and mixing depths. Under certain weather conditions, surface and low-altitude inversions are especially frequent and intense, and mixing depths and ventilation rates are severely limited. Such conditions occur most frequently in slow-moving or stationary high-pressure systems (anticyclones). The frequency of such systems in the United States east of the Rocky Mountains has been summarized by Korshover (1960). Murray and Trettel (1966) examined the frequency of these weather systems specifically for northeastern Illinois between 1936 and 1964 with somewhat different results. Both determinations were based on the technique described by Korshover (1960), which identifies locations affected by stagnating high-pressure systems from weather map indications of geostrophic winds.*

Korshover considered only situations where stagnations persisted for four days or more. Murray and Trettel (1966) also summarized 2- and 3-day stagnations (Table 24). However, days with fronts in the area or with mean daily wind speeds over 3.6 m/sec (8 mph) or 0.25 mm (0.01 in.) or more of precipitation at Midway Airport, Chicago, were excluded. Two-day stagnations occurred in all months of the year during the period 1936-1964; August and July, with 31 and 27 stagnations, respectively, were the months of maximum frequency. Three-day stagnations occurred much less frequently, with 12 and 8 in July and August, respectively. August was also the month with the highest number of stagnations--seven--of four days or more. The distributions of total stagnations and total days of stagnation were very similar. Both parameters peaked in August, and in both instances the next three months of greatest frequency were July, October, and September. These four months accounted for 75% of all stagnations and 76% of all days with stagnations.

Table 24. Annual Distribution (Number of Occurrences) of Nearly Stationary Anticyclones in Northeastern Illinois, 1936-1964 (Data from Murray and Trettel, 1966)

	Stagnation Duration, days						*Total Cases*		*Total Days*	
Month	*2*	*3*	*4*	*5*	*6*	*12*	*No.*	*%*	*No.*	*%*
January	1						1	0.5	2	0.4
February	3						3	1.6	6	1.2
March	3	1					4	2.2	9	1.9
April	5	1	1				7	3.8	17	3.6
May	2	1					3	1.6	7	1.5
June	13	1	3	1			18	9.7	46	9.6
July	27	12	3	1			43	23.2	107	22.4
August	31	8	4	2		1	46	24.9	124	26.0
September	13	7	2	2			24	13.0	65	13.6
October	19	3	1	2	1		26	14.0	67	14.0
November	3	2	1				6	3.2	16	3.4
December	3			1			4	2.2	11	2.3
Totals	123	36	15	9	1	1	185	100.0	477	100.0

**A ficticious wind calculated from the spacing of lines of constant pressure on a weather map. It approximates actual winds above the layer affected by surface friction, or at about 1000 m.*

The numbers of stagnations of various durations to be expected in northeastern Illinois in a year are shown in Table 25. A total of about six stagnations should be expected. Four of these should last two days each, one three days and one four days or more. Three-fourths of the annual stagnations should occur during the months of July through October.

Table 25. Expected Number of Stagnations Occurring for Two, Three, Four, or More Days in Northeastern Illinois (Data from Murray and Trettel, 1966)

Stagnation Duration, days	*Expected Number per Year*
2	4.2
3	1.2
4 or more	0.9
Total	6.3

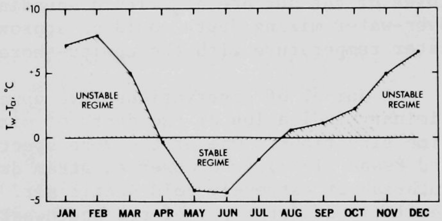
We have been concerned with stagnation frequencies chiefly because they are large-scale weather systems that feature strong and frequent inversions and very limited vertical mixing over large areas. These statements apply primarily to land areas away from large water bodies. Conditions over and near large water bodies are frequently so different from conditions over land as to require special consideration.

INFLUENCES OVER AND NEAR THE LAKE

The fundamental physical reason for differing dispersion conditions over and near large water bodies lies in the nature and differential temperature of the water surface, compared to land surfaces. In winter, the largely unfrozen Lake reaches a minimum temperature of 0°C (32°F), while land surfaces can be several tens of degrees colder. The opposite occurs in the summer, when land surface temperatures can greatly exceed those of the lake surface. The annual cycle of water-air temperature differences is shown in Figure 63. The unstable regime extends from August to March, reaching a peak in February, while the summer stable regime extends from April into July with its maximum in June.

Fig. 63.

Annual Cycle of Stability Regimes in the Lowest Air Layer over Lake Michigan. Data from Ayers (1962), quoting Hunt (1958--unpublished).



Land-lake temperature differences also manifest themselves in two other ways: in large horizontal differences in air temperature across the shoreline, and in respective vertical temperature distributions above lake and land. In the summer, for example, surface-air temperatures over the water are low compared with those over land. This imbalance in temperature, and thus density, frequently results in the subsidence and spreading of the cool lake air over adjacent land areas in the summer, the well-known lake breeze. Also, the low air temperatures near the lake surface create a very stable condition over the water, whereas the high surface temperatures over land create instability in the lower atmosphere. The low-level stable layer over the Lake has important consequences for pollutants released into this layer, as well as for surface deposition of aerosols in higher layers.

Land areas near the Lake are also subject to unusual dispersion conditions whenever lake-cooled air flows over them. This may happen in lake-breeze situations, or during flow from Lake to land in response to the large-scale pressure distribution. In such onshore flows, a number of generally poor dispersion conditions can occur. Power plants and industries frequently find lakeshore locations attractive because of the abundance of water available for their operations. Lakeshores also tend to be rather densely populated. Thus, poor dispersal conditions occur frequently in an area of both strong pollutant sources and high population density. It is therefore important to consider, in some detail, dispersion conditions both over the Lake and over nearby land areas.

Over the Lake

Dispersion capabilities of air over Lake Michigan, like most large water bodies, are poorly known and need further research. In general, however, the lowest air layer over the Lake may be characterized as having two main stability regimes during the year: the winter regime, and the summer regime.

The winter regime is unstable, with cold air flowing over a relatively warm Lake. The depth of the unstable layer is not well characterized, but would be expected to increase with distance from the upwind shore and with difference in temperature between the lake surface water and surface air at the upwind shore.

The development of the mixed layer, with distance from the upwind shore, in cold air flowing over a warm lake can perhaps be likened to temporal development of the mixed layer over land on a sunny day. As cold air is warmed by contact with warmer water, the depth of the mixed layer might be approximated by intersections of successive dry adiabats drawn through successive temperatures of the surface air with a sounding at the upwind shore. The maximum over-water mixing depth would be approximated by intersection of the surface-water temperature with the upwind-shore sounding.

A number of observations have appeared in the literature that give a preliminary indication of the depth of mixed layers over Lake Michigan in wintertime situations. One of the more spectacular observations was that of Lyons and Pease (1972), who observed steam devils a few km off Milwaukee during an outbreak of extremely cold Arctic air. The steam devils, analogous to dust devils in desert areas of the southwestern United States, were estimated to have reached heights of 460 m ($\sim$1500 ft). This would be a lower limit of the mixing depth over water on this occasion. Cumulus clouds were present above the steam devils, indicating even deeper mixing. In this instance, the height of the mixing was increased an unknown amount by release of the latent heat of condensation in the clouds.

A second observation (Lyons, 1975) also pertains to over-water mixing with cloud formation. In this instance, cumulus clouds, reported by a pilot to have had tops of 820 m (∿2700 ft) above the surface, appear to have been enhanced by smoke plumes from the Chicago-Gary industrial region.

The summer regime over Lake Michigan is stable, with warm air above relatively cooler water. The flowing warm air gradually loses heat by conduction to the cool surface, forming an intense inversion near the surface. An example of such an inversion measured northward from the southern end of Lake Michigan is shown in Figure 64 (Bellaire, 1965). The inversion was confined to the lowest 100 m (∿330 ft) of air above the Lake on this occasion. Summer conduction inversions range in height from 100 to 150 m (∿330 to 500 ft) (Cole and Lyons, 1972) throughout the warm season, but their intensity (change in temperature per unit height) gradually decreases during the summer as the lake surface warms (Lyons *et al.*, 1974).

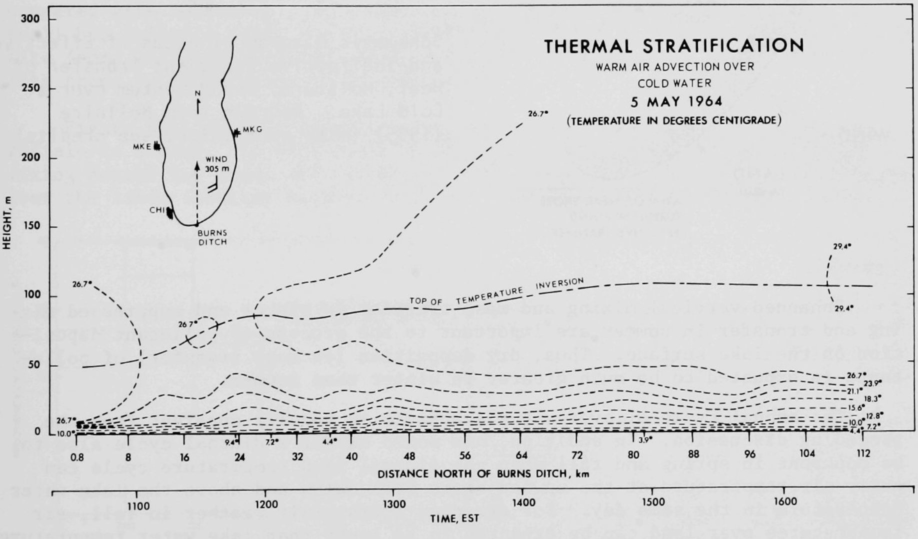


Fig. 64. Temperature Cross-Section over Lake Michigan Obtained by Wiresonde, 5 May 1964. Modified from Bellaire (1965) (with permission, see credits).

Important changes in wind speed and direction occur in the lake stable layer, compared to winds at comparable heights over nearby land areas. For both speed and direction, the presence of the very stable air layer causes land-lake differences unlike those that might be expected under less stable conditions. In the case of wind direction, a decrease in surface roughness from land to Lake would be expected to cause a clockwise shift (a veering wind). In actuality, wind direction responds to a lake-scale high-pressure system within the stable layer, centered near the lee shore (Lyons *et al.*, 1974). Thus, the land-lake shift in wind direction is a complicated function of location and the local and macro-scale pressure distributions. Wind speed might be expected to increase over the Lake in response to the smoother lake surface; in reality, the speed invariably decreases in stable situations (Lyons *et al.*, 1974; Bellaire, 1965; Strong and Bellaire, 1965) due to a lack of downward momentum transfer from the faster moving air above the lake inversion.

The suppression of momentum transfer in the summer cold dome over the Lake is accompanied by a corresponding suppression of heat and mass transfer via turbulent motions. A schematic diagram [Bellaire (1965)] showing areas of effective and ineffective turbulent transfer over a large lake in summer is shown in Figure 65.

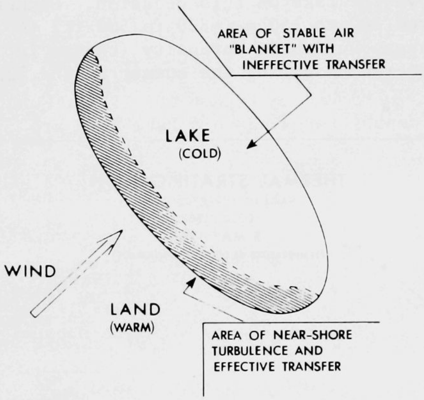


Fig. 65.

Schematic Diagram of Areas of Effective and Ineffective Turbulent Transfer of Heat, Moisture, and Momentum over a Cold Lake. Redrawn from Bellaire (1965) (with permission, see credits).

Enhanced vertical mixing and mass transfer in winter and suppressed mixing and transfer in summer are important to the process of pollutant deposition on the lake surface. Thus, dry deposition (or mass transfer) of pollutants is expected to be much greater in winter than summer.

The annual cycle of over-water stability is readily apparent from the preceding discussion. In addition, one would expect a diurnal cycle also to be apparent in spring and fall when the diurnal land temperature cycle can carry air temperature at the upwind shore both below and above the lake water temperature in the same day. For example, during fair weather in fall, air temperatures over land can be expected to be lower than lake water temperature during the night and higher during midday. This should produce relatively unstable air over the Lake at night and relatively stable air during the day.

Our discussion of stability regimes over the Lake is important to dispersion and deposition of pollutants over the Lake and on the downwind shore, from large sources. However, of even greater importance is the lake effect on pollutant dispersal on the same shore and inland, from the same large sources. The occurrence of onshore flow brings lake air, and its stability regime, over land areas with both strong pollution sources and high population density.

Over Near-Shore Land Areas

The extreme differences in the stability of the air over the Lake between winter and summer result in equally extreme differences in dispersion conditions when lake air moves inland. We shall treat the simpler winter situation first, and then deal with the more complex summer situation, which can frequently lead to severe pollution situations over near-shore land areas.

The most spectacular effect of lake air moving inland in winter is the lake-effect snow storm. These occur during outbreaks of very cold air, when air-water temperature differences are large; deep mixing and large vertical transport of water vapor from the lake surface form clouds that precipitate snow over the Lake and adjacent lee shores. Snow from these events can range from showers to extremely heavy accumulations.

The lake-effect snow storm is an example of extremely unstable air moving over downwind shores. Of course, a whole spectrum of stabilities occurs in air moving over shore areas from the Lake. The overall effect on the mixing depth during onshore flow is a shift of mixing depth frequency spectrum toward higher values than otherwise occur, as illustrated in Figure 66a (after Munn, 1975--unpublished) for Buffalo. Mixing depths for winds off Lake Erie are compared with all other wind directions at Buffalo in winter. There is a small but definite shift toward higher mixing depths at the Buffalo radiosonde site (some kilometers inland) when airflow is off Lake Erie. Just the opposite trend is found during the warm season.

Figure 66b compares frequency distributions of mixing depth heights at Buffalo in summer. In this case, there is a systematic shift toward lower mixing depths for winds off the water, a reflection of the summer stable layer over the lake. Similar results would be expected near Lake Michigan shores.

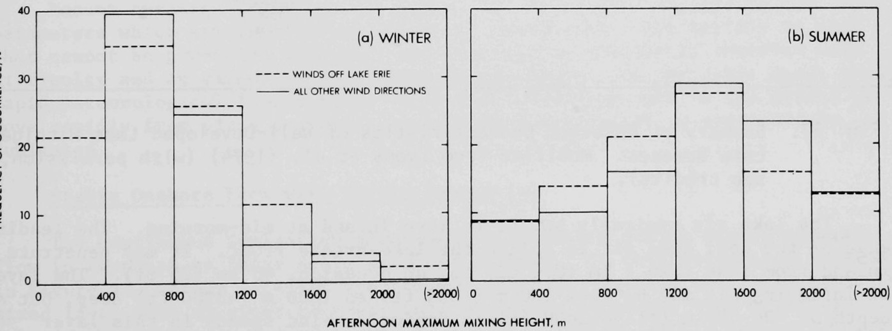


Fig. 66. Comparison of Afternoon Mixing Height Frequencies for Winds off Lake Erie and All Other Wind Directions at Buffalo. Based on Munn (1975--unpublished).

The observed shift in mixing depths during onshore flow is a statistical integration of several distinguishable mixing-height limiting mechanisms. These mechanisms are (*i*) lake-breeze circulations, (*ii*) stable onshore flow on sunny days, and (*iii*) stable onshore flow at night or on cloudy days. Each of these has different effects on pollutant plumes. Together, these dispersion-limiting events occur on approximately two-thirds of all days during spring and summer in the Chicago-Milwaukee area (Cole and Lyons, 1972). They will be treated in order in the following paragraphs, borrowing heavily from Cole and Lyons (1972) and Lyons *et al.* (1974).

Lake-Breeze Circulations

Lake breezes typically develop on spring or summer days with light winds, strong sunshine, and warm afternoon temperatures over land. Their main features are summarized in Figure 67.

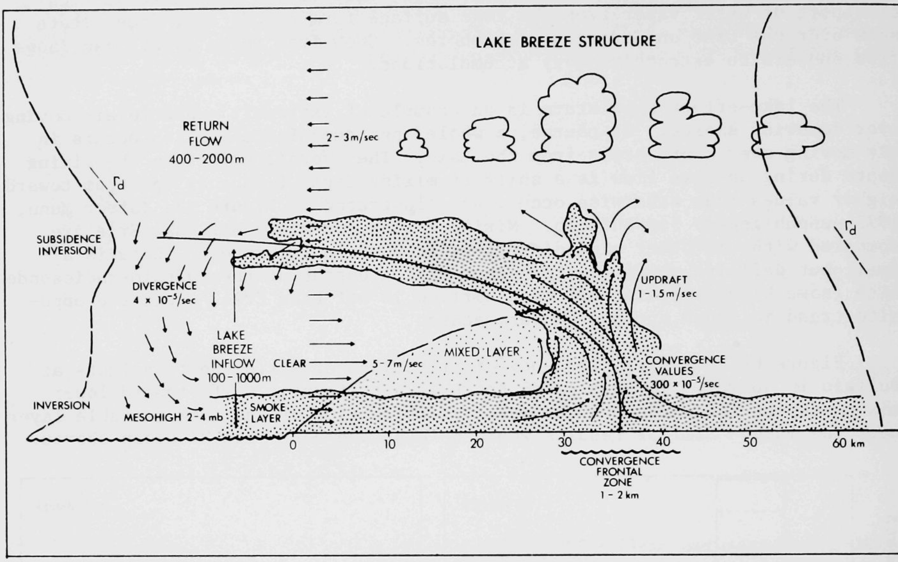


Fig. 67. Summary of Observed Characteristics of Well-Developed Lake Michigan Lake Breezes. Modified from Lyons *et al.* (1974) (with permission, see credits).

The lake air typically begins to move inland at mid-morning. The leading edge of the cool lake air is called the lake-breeze front. It may penetrate inland from less than 1 km (0.6 mi) to, on occasion, 40 km (25 mi). The layer of inflowing air may be from 100 m (~330 ft) to 1000 m (~3300 ft) deep, but a depth of 400-500 m (~1300-1600 ft) is typical. Wind speeds in this layer reach 5-7 m/sec (16-23 ft/sec) at most, but evidently always exceed the speed of the front itself, typically a few m/sec. Inflowing air, upon overtaking the front, is forced upward in the convergence zone, along with inland air being undercut by the denser lake air. Updraft speeds of 1 to 1.5 m/sec (3 to 5 ft/sec) are common. A return flow layer is present above the inflow layer; it is about twice as deep as the inflow layer, with about half the wind speed. Although Figure 67 suggests two-dimensional flow, lake-breeze flow is really three-dimensional, with a component into or out of the plane of the paper. Thus, recirculated air follows a broad, flat, helical path.

Typical temperature profiles over water and land are shown (dashed lines) at the respective edges of Figure 67. Over the water, a shallow (100 m) inversion is present just above the surface. A second inversion may be present near the top of the inflow layer (the mesoscale subsidence inversion caused by air in the return flow sinking over the Lake). Still a third inversion is likely to be present at higher levels, over both land and water. This is the large-scale subsidence inversion associated with the high-pressure system whose clear skies and light winds favor lake-breeze development. Over land, a deep adiabatic layer is likely, capped by the large-scale inversion.

Lake breezes occur in the Chicago-Milwaukee area on 35% of spring and summer days (Lyons, 1972). Sixty percent of them cross the shoreline between 0700 and 1200 CST, most often between 0800 and 0900. Forty percent of Chicago lake breezes penetrate inland as far as 15 km (9 mi); a few each year reach 30 km (19 mi) inland. Further inland than a few kilometers, the lake breeze is best identified by the wall of smoke and its wind shift (Lyons, 1972), because the temperature contrast across the lake-breeze front is very small.

An important feature of lake-breeze structure for pollution dispersal is the layer of well-mixed air that begins to develop over land near the shore, and gradually deepens as the inflowing lake air is heated more and more by the land surface. Pollutants released from surface sources or short stacks within this layer will be rapidly mixed. A pollutant plume from tall stacks near the shore will be carried along in the stable onshore flow until the mixed layer grows up into it. Then materials in the plume will be rapidly mixed to ground level, causing high pollutant concentrations. This process is known as fumigation. Pollutants from large sources at the shore can be continuously fumigated to ground level in high concentrations. Lyons and Cole (1973) have proposed a numerical model for such phenomena.

Recent research (Lyons *et al.*, 1974) has shown that meteorological input parameters which strongly affect the model results can vary rapidly in ways that cannot be predicted very well and can only be adequately observed with difficulty and an extensive field monitoring effort. On the other hand, these rapid meteorological fluctuations cause the fumigation spot on the ground to move rapidly from place to place, so that no one location is continuously fumigated.

Stable Onshore Flow with Strong Insolation

The continuous fumigation phenomenon also occurs during summer onshore flow in response to large-scale pressure systems. In this situation, diagrammed in Figure 68, strong sunlight again heats the land, causing the formation of a mixed layer with an upper boundary that increases in height with distance inland. No convergence zone forms, because all surface air is moving in the same direction at moderate speed.

The presence of the well-mixed internal boundary layer means that pollutants released within the layer will mix rapidly within the layer, as in the lake-breeze case. Plumes intersected by the upward-growing mixed layer also fumigate to the ground. In a few cases examined in detail in the Milwaukee area, Lyons *et al.* (1974) reported that the worst fumigations of plumes from tall stacks at the lakeshore occurred under this category of stable onshore flow. Fumigations with lake breezes also occurred, but the greater variability of several meteorological parameters under such conditions served to lessen the impact. These authors also reported that stable onshore flow with strong insolation occurs on about 15% of spring and summer days in the Chicago-

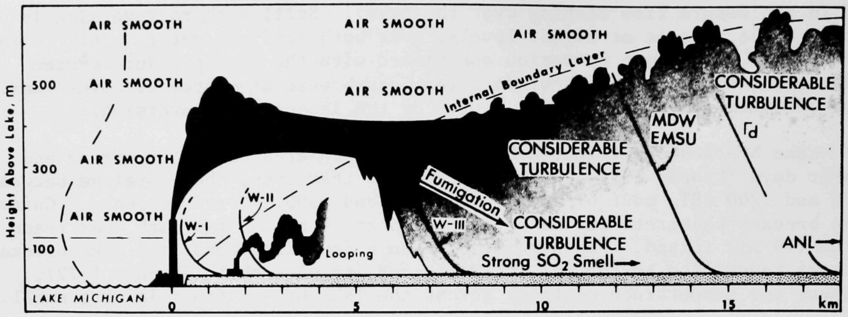


Fig. 68. Summary of Observed Characteristics of Stable Onshore Flow with Strong Insolation. MDW = Midway Airport (Chicago); EMSU = Environmental Meteorological Support Unit. Modified from Lyons and Cole (1973) (with permission, see credits).

Milwaukee area. This regime should be more common on the east (Michigan) shore of Lake Michigan since prevailing summer winds have a westerly component (Fig. 32).

Stable Onshore Flow at Night or with Cloud Cover

Stable onshore flow at night or with cloud cover occurs when the large-scale pressure pattern causes a moderate onshore flow but strong sunshine is lacking. This precludes the development of a surface mixed layer. Figure 69 is a schematic representation of such a case near Milwaukee. On 27 May 1970, several kilometers of warm surface water near shore gave rise to the shallow unstable layer in the lake air. In the absence of strong insolation, this layer was maintained over land, causing a near-surface plume to mix thoroughly in the shallow layer while the upper-level plume remained relatively undiluted at its equilibrium altitude.

Other variations of this situation can be imagined. For example, if the lake air was stable all the way to the surface, perhaps a shallow mixed layer would form over land in response to a land surface warmer than the water surface. Or, for flow over a city, the urban heat island might cause a shallow mixed layer to develop. In all of these cases, fumigation of plumes from tall stacks would be unlikely.

Summary

The geographical location of the Lake Michigan region assures generally good dispersion conditions in locations well away from the Lake. A completely different situation exists near the Lake, however, where dispersion conditions can range from good to poor, depending mostly on the season of the year.

Well away from the Lake, inversions occur in the lowest 150 m (500 ft) of the atmosphere about one-third of all hours, in all areas of the region, and in all seasons. Nevertheless, large variations in frequency occur on a daily

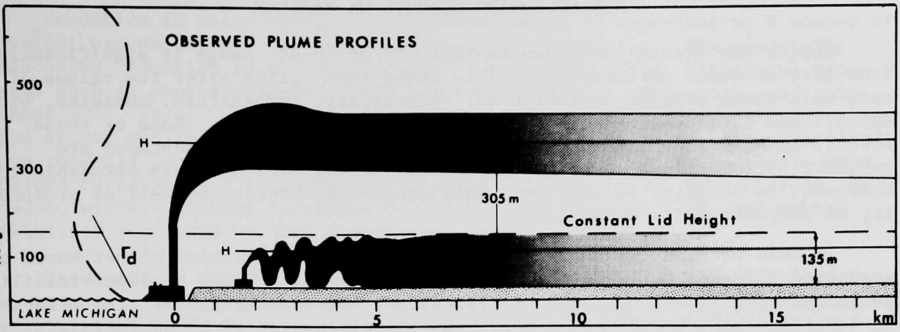


Fig. 69. Schematic Diagram of Plume Behavior during Stable Onshore Flow at Night or with Cloud Cover. Slightly modified from Cole and Lyons (1972) (with permission, see credits).

basis. Low-level inversions are very frequent during the night hours, and almost totally absent during the mid-part of the day. In cities, inversions above rooftop level are less frequent and less intense than in nearby rural locations.

Maximum afternoon mixing depth shows little variation across the region, but in Chicago, the mixing depth is deeper than in nearby rural locations by an average of 200-400 m (∿700-1300 ft) both at sunrise and in the afternoon.

Air stagnations are expected in the region about six times a year. Four of these should last for only two days, one for three days, and one for four days or more. Three-fourths of the stagnations normally occur between July and October.

The Lake has very distinct influences on pollutant concentrations. These are felt especially on near-shore land areas. In winter, the Lake is warmer than the air flowing over it. This creates a very unstable layer of air near the surface. Its depth is not well documented, but 1000 m (∿3300 ft) is an approximate upper limit. In this layer, mixing is vigorous and dispersion is good.

In summer, the water is relatively cold and a very stable layer, 100-150 m (∿330-500 ft) deep, is found over the Lake. This stable layer limits mixing over the Lake and has very pronounced effects when it moves over near-shore land areas. Its general effect is to decrease average mixing depths, but specific phenomena, such as the lake breeze, have their own characteristic pollution effects. The worst of these is the continuous fumigation of elevated sources along the lakeshore to ground level within a few kilometers of the Lake.

AIR POLLUTION EFFECTS ON WEATHER

Cities can create their own weather, or at least change it significantly from that of their surroundings. This means that cities alter the values of such well-known weather variables as: visibility, temperature, humidity, wind speed, wind direction, precipitation, and frequency of fog. Some of these reflect changes in the landscape caused by cities. These landscapes are rougher, aerodynamically, so air flow is affected; they are less permeable to moisture, so humidity is affected; they store heat better, as well as produce it, so temperature is affected.

In this section, we shall only consider weather variables either known or suspected to be directly affected by air pollutants.* These include visibility, sunshine, cloudiness, fog, and precipitation. For discussion of city effects on other weather variables, or more complete discussion of those included here, see reviews by Peterson (1969), Landsberg (1970), or Oke (1974).

This section first describes what is known in general about direct air pollution effects on weather. It continues with a review of the limited information available on effects in the Lake Michigan region, and concludes with a brief consideration of possible future effects on weather by large power parks.

GENERAL EFFECTS

Landsberg (1962, 1970) has provided two comprehensive reviews of urban effects, including air pollution, on weather and climate. Table 26 summarizes his findings for those variables known or suspected to be directly affected by air pollution.

Table 26. Urban Air Pollution Effects on Weather
(Data from Landsberg, 1962, 1970)

Weather Variable	*Change from Rural Surroundings*
Solar radiation	
Total on horizontal surface	15% less
Ultraviolet, average	30% less
Ultraviolet, winter	Over 30% less
Horizontal visibility	Up to 90% less
Fog frequency	200-500% more
Cloudiness	5-10% more
Precipitation	
Average amount*	10% more
Thunderstorm rainfall*	30% more

**In downwind area of maximum increase, which may be outside of the city.*

Changes in solar radiation and visibility, the first two weather features listed, are the result of increased concentrations of airborne particulate matter in cities. The optical properties of airborne particles reduce both the amount of sunlight reaching the ground, and the distance one can see.

**Not including heat and moisture pollutants.*

Reduction in solar energy reaching the ground is important to a number of physical processes, such as photochemistry and visibility. The especially pronounced reduction in the shorter wave lengths can affect biological processes such as photosynthesis, human tanning, vitamin D production, and skin cancer (Oke, 1974). Visibility reduction, including fog, affects transportation safety and aesthetic values. In cities where particulate concentrations have recently dropped because of air pollution control measures, people have noticed corresponding increases in sunshine and visibility. For example, in London, winter sunshine increased by 70% between 1960 and 1970, and winter visibility increased by 300% (Landsberg, 1970).

Increases in cloudiness tend to reduce surface heating, resulting in a more stable vertical temperature structure. Increased precipitation and severe weather are important in urban storm sewer design and agricultural yields.

LAKE MICHIGAN REGION EFFECTS

Investigations of air pollution effects on weather in the Lake Michigan region are very limited. Those available pertain to the Chicago-northwest Indiana area.

Moses (1976--unpublished) compared total solar radiation on a horizontal surface for sites at Argonne National Laboratory and downtown Chicago. He found that 5-10% less radiation reached the surface at the city location. An excellent illustration of the reduction of solar radiation in city air on a single occasion is shown in Figure 70. This situation had the appearance of a lake breeze reaching Argonne just before 1330 on 19 March 1969. Actually a lake-accelerated southwestward moving cold front was involved, but the result was the same, *i.e.* polluted air from Chicago (trapped in a shallow internal boundary layer in onshore flow) reached Argonne. Solar radiation rapidly

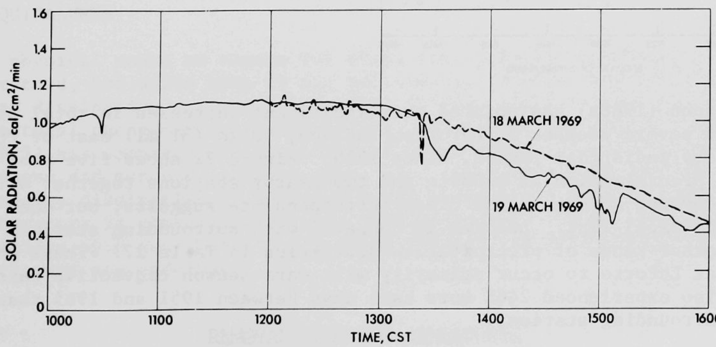


Fig. 70. Solar Radiation Data for Argonne National Laboratory Showing Effect of Pollutants in Reducing Insolation Following Cold Front Passage at about 1330 hrs. Chart trace for the previous day is shown for comparison. Slightly modified from Carson and Nelson (1969).

dropped 15-20% and the reduced value persisted for several hours. The pyrheliometer trace from the virtually cloudless previous day is included for comparison (Fig. 70).

Direct evidence that pollutants can cause increased cloudiness was shown by Lyons (1974). He presented satellite photographs of enhanced cloudiness over Lake Michigan in industrial smoke plumes from the Chicago-Gary area. These local effects are undoubtedly related to the content of heat, moisture, and/or cloud nuclei in the plumes. However, specific physical causes of the enhanced cloudiness on a regional scale are harder to isolate.

There is increasing evidence that cloudiness is changing, not only in large cities, but in smaller ones as well. For example, the time trends of days with clear, partly cloudy, and cloudy skies at Peoria are shown in Figure 71. Notice the rapid increase in the frequency of cloudy skies, and the corresponding large drop in clear sky frequency, in the early 1940's. Similar data for Chicago were presented in Figure 35.

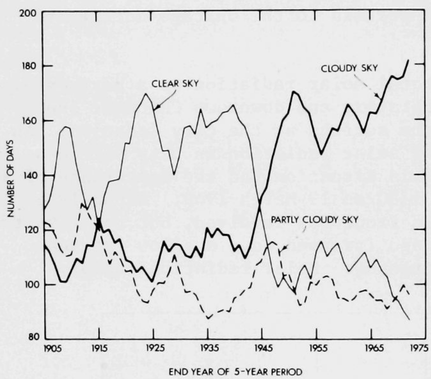


Fig. 71.

Five-Year Moving Averages of Annual Number of Days with Cloudy, Partly Cloudy, and Clear Skies at Peoria, Illinois. Slightly Modified from Changnon (1974) (with permission, see credits).

Changnon (1968a) has pointed out significant increases in total precipitation and severe weather at LaPorte, Indiana, 50 km (31 mi) east of the Chicago-Gary indistrial region, since 1925. Figure 72 shows five-year moving totals of precipitation at LaPorte and two nearby stations together with smoke and haze days at Chicago. The close correspondence suggests, but does not prove, a physical link. LaPorte is compared with surrounding stations in terms of other kinds of precipitation statistics in Table 27. These show the increase at LaPorte to occur primarily with warm-season convective rainfall. LaPorte also experienced 246% more hail days between 1951 and 1965 than the mean of surrounding stations.

Controversy surrounding the validity of the LaPorte data led to the comprehensive investigations of possible precipitation anomalies in eight other cities (Huff and Changnon, 1973) using available data and the very extensive METROMEX measurement program at St. Louis (Changnon *et al.*, 1971). These studies have confirmed that large cities cause excessive precipitation in downwind locations.

Fig. 72.

Five-Year Moving Totals of Precipitation Values at Selected Indiana Stations and Smoke-Haze Days at Chicago. Modified from Changnon (1968a) (with permission, see credits).

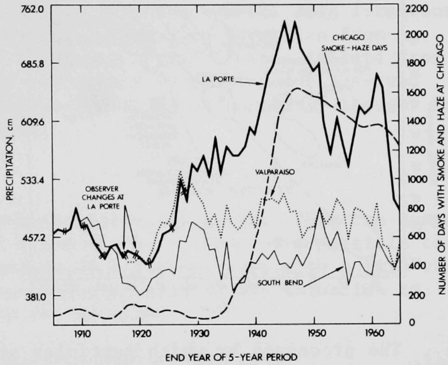


Table 27. Difference between Average LaPorte Weather Values for 1951-1965 and the Means at Surrounding Stations (Changnon, 1968a)

Weather Conditions	*Percent of the Means*
Annual precipitation	31
Warm season precipitation	28
Annual number of days with precipitation ≥ 0.25 inch	34
Annual number of thunderstorm days	38
Annual number of hail days	246

ENERGY EQUIVALENTS

The physical cause or causes for these precipitation increases are not yet understood, but urban heat or air pollutants, or both, may be involved. Urban heat dissipation, although sizeable, is less concentrated than such violent natural phenomena as thunderstorms, volcanoes, and forest fires. Slinn (1975) has compared the intensity of power dissipation of several natural phenomena and man-made systems (Fig. 73). He pointed out that the intensity of energy dissipation by proposed power parks containing several nuclear power generators is comparable to some rather violent natural phenomena. Investigations into possible effects, both harmful and beneficial, of such power parks are now underway.

REMOVAL FROM THE ATMOSPHERE

The final stage in a pollutant's life cycle in the atmosphere, after emission and dispersal, is removal. Removal processes are important to air pollution climatology because they determine how long pollutants remain airborne, as well as where and in what concentrations they are deposited on the earth's surface. Thus, they are a system of important links in pollutant pathways from sources to potentially vulnerable receptors. These receptors can include man, as well as terrestrial and aquatic ecosystems.

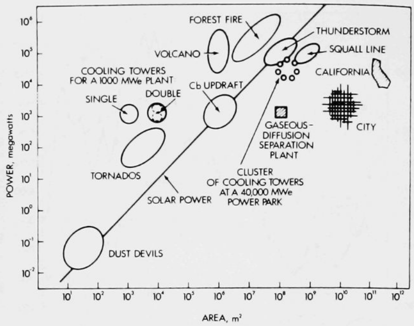


Fig. 73.

Qualitative Plot of Power Dissipated by Various Natural and Anthropogenic Activities as a Function of Their Scale Size. Slightly modified from Slinn (1975) (with permission, see credits).

The processes by which particles are removed from the atmosphere (Junge, 1963) include (*i*) "wet" (precipitation) processes and (*ii*) "dry" processes, including sedimentation and impaction on the earth's surface or near-surface obstacles. The processes by which gases are removed from the atmosphere (Junge, 1963) include (*i*) precipitation processes, (*ii*) sorption or reaction at the earth's surface, and (*iii*) conversion into particles or other gases by chemical reactions in the atmosphere.

Our present knowledge about the temporal and spatial variation in removal rates is quite limited. It is not possible, for example, to present maps showing average dry and wet deposition rates across the Lake Michigan region, or to show their average daily variation at a single location. Nevertheless, some estimated dry and wet deposition inputs of various elements to Lake Michigan have appeared in the literature. The purpose of the next section is to discuss briefly the various physical processes involved in removal mechanisms. We will first discuss transformation processes in the atmosphere; this is followed by summaries of wet and dry deposition.

TRANSFORMATIONS

This subsection discusses those processes by which gases in the atmosphere are removed by conversion, either to other gases or to solid particles. In such processes, removal refers not to removal of mass from the atmosphere, but to the conversion of one molecular form into another.

These mechansims play a large role in air pollution by converting the pollutant gases emitted by man's activities into more noxious forms. Photochemical smog and airborne sulfates are two well-known products. Another is the blue haze that makes the Smoky Mountains smoky. The "smoke" is an aerosol of fine particles produced photochemically from terpenes given off by vegetation.

There are two general types of transformations to be considered, those starting only with gaseous components, and those in which particles are needed to make the transformation occur.

Homogeneous Reactions

In homogeneous transformations, gases react with each other in the absence of solid particles. The reaction products may be either gases or particles. Sunlight is generally required in reactions of significance in air pollution.

An example of this kind of transformation is photochemical smog formation from gaseous hydrocarbons and nitrogen oxides. Blue haze formation from terpenes is also in this category. The formation of particulate sulfate from SO_2 occurs by this process, but probably too slowly to account for observed atmospheric sulfate concentrations. Sulfate formation is currently thought to occur primarily by heterogeneous processes.

Heterogeneous Reactions

Heterogeneous reactions involve both particles and gases. They can range in complexity from simple absorption of a gas on the surface of a particle to reactions involving catalysts on the surface of a particle wet with a film of water. The latter is exemplified by a possible process of SO_2 oxidation to sulfate, which is given schematically by the equation

$$SO_2 + (\tfrac{1}{2}O_2)_{(aq)} + H_2O \xrightarrow[\text{catalyst}]{} 2H^+ + SO_4{}^{2-} \ . \qquad (1)$$

This general reaction is currently the subject of a great deal of research to explain how SO_2 oxidation and removal occurs in the atmosphere. Another possible process is dry deposition.

DRY DEPOSITION

Dry deposition may be defined as the elimination of airborne substances from the atmosphere by all mechanisms other than precipitation. It includes such processes as gravitational sedimentation, impaction on surface obstacles, and absorption of gases on ground surfaces.

Dry deposition has been estimated to account for about half of the total deposition of airborne materials. For example, dry processes account for 40% of the Pb deposition in New York City (Krey and Toonkel, 1976--in press). However, the problem of how well artifical collection surfaces measure actual dry deposition causes considerable uncertainty in these estimates.

With reference to Lake Michigan, dry deposition on the Lake itself must obviously be considered when assessing the role of the atmosphere in polluting the Lake. However, the possibility exists that dry deposition on vegetation in the watershed, followed by runoff into the Lake, also makes a contribution (Winchester, 1976).

Although dry deposition includes several different physical mechanisms (named above), the estimation of dry deposition commonly treats only the sum of these subprocesses, using the deposition velocity V_d (cm/sec) given by:

$$V_d = \frac{D}{\chi} \ , \qquad (2)$$

where D is deposition (g/cm^2/sec), and χ is concentration (g/cm^3). It is clear that if one has an estimate of V_d and a measurement or estimate of χ, an estimated D may be calculated.

V_d is evaluated empirically from measurements of D and χ. There is, unfortunately, a serious problem in measuring D on natural surfaces. For one thing, natural surfaces such as trees or lake surfaces are either contaminated or hard to sample, or both. Also, there is such a wide variety of natural surfaces that large numbers of samples would be necessary, if such sampling were feasible, to make valid estimates of deposition, even in a small area.

To avoid these problems, two approaches have been used. One is to simulate actual conditions using a wind tunnel and simple (usually artificial) deposition surfaces. The other is to sample in the atmosphere, again using a simple but artificial surface.

Results for the deposition of atmospheric particles on filters shielded from rain were given by Cawse (1974), and are shown in Figure 74. The results of Sehmel and Sutter (1974), for particle deposition on a water surface in a wind tunnel, are given in Figure 75 with Cawse's data superimposed. While neither set of data matches exactly the situation of dry deposition from the atmosphere to a real lake surface, it is of interest to see what differences exist between the two results.

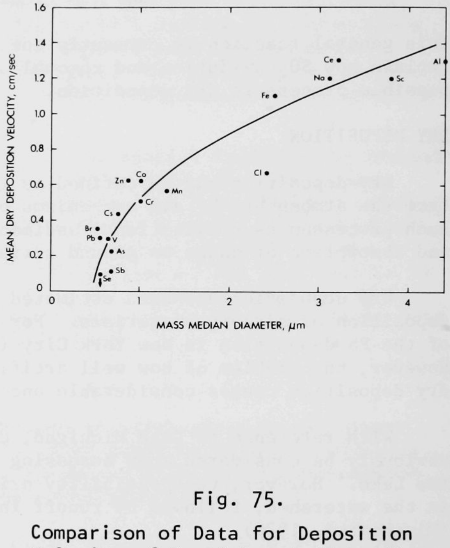


Fig. 74.

Variation of Dry Deposition Velocity, V_d, with Particle Size. Drawn from data of Cawse (1974). From Gatz (1975) (with permission, see credits).

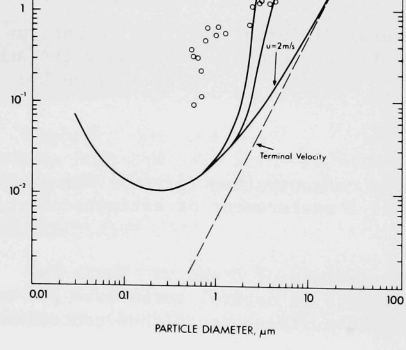


Fig. 75.

Comparison of Data for Deposition Velocity of Particles to Water Surfaces (Sehmel and Sutter, 1974) with Measurements of Dry Deposition to Shielded Filter Pads (Cawse, 1974). Data of Cawse are represented by data points on the graph of Sehmel and Sutter. Graph redrawn from Sehmel and Sutter (1974) (with permission, see credits).

Both results show increasing V_d with particle diameter above 0.3 μm, but still there are substantial differences between results. Cawse's values for filter paper deposition exceed wind tunnel deposition on water by factors between 7 and 40 for elements with mass median diameters (MMD's) between 0.5 and 1.3 μm. For elements with larger mass, there may be substantial agreement, if average ambient wind speeds were as high as 7 m/sec (23 ft/sec).

Overall, atmospheric deposition of real atmospheric particles on filter paper appears to exceed wind tunnel results for deposition on water. The differences are reduced (Chamberlain, 1976) if one recalls that the wind tunnel experiments were conducted with particles of a single size, whereas atmospheric elements are polydisperse (*i.e.* reside on a range of particle sizes). For such a spectrum, the mean V_d will ordinarily be larger than that given by the MMD because larger particles contribute disproportionately to the mean V_d. Further, Wilson (1975--unpublished) has shown that some elements have bimodal distributions, and that for these elements, the concept of mass median diameter may not be appropriate. Chamberlain (1976) also compared Cawse's field measurements to wind tunnel deposition on filter papers, and still found somewhat of a discrepancy.

In summary, the V_d's measured in the field on filter papers exceed wind tunnel measurements of V_d on water by more than can be accounted for by the difference in deposition surfaces and the fact that atmospheric particles are not all a single size. These studies suggest that wind tunnel results could be taken as a lower limit for V_d providing one properly accounts for the size spectrum of atmospheric particles when applying the result.

The discussion so far has dealt only with dry deposition of particles. Dry deposition of gases also may be estimated using deposition velocity, although fewer estimates of V_d are available for gases than for particles. Van der Hoven (1968) concluded that V_d = 2 cm/sec (0.8 in./sec) was an appropriate upper limit for deposition of ^{131}I on grass or water, with values ranging down to 0.5 cm/sec (0.2 in./sec) for soil or snow surfaces. Chamberlain (1960) calculated an average value of V_d = 1.8 cm/sec (0.7 in./sec) for SO_2 deposition, dry and wet combined, in Britain.

WET DEPOSITION

For particles, current evidence suggests that wet and dry deposition each account for about half of the total mass removed from the atmosphere. This does not mean, necessarily, that the relative importance of dry and wet processes is the same for all particle sizes. It may be that one or the other is predominant for certain particle sizes. There is also the question of the relative removal of gases by dry and wet processes. These questions have not yet been settled by research.

The description of the physical processes by which precipitation removes impurities from the atmosphere must proceed in steps, according to the nature of the impurity and type of precipitation. Thus the wet removal, or scavenging, of gases is considered separately from that of particles. For both, rain and snow are considered separately. Finally, both in-cloud and below-cloud processes can sometimes be distinguished.

PHYSICS AND CHEMISTRY OF PRECIPITATION SCAVENGING

Gas scavenging has only recently received the attention of researchers, because of concern about atmospheric SO_2. Earlier research had concentrated on particle scavenging, largely because nuclear bomb debris was primarily in particulate form.

For a gas to be scavenged by precipitation, it must first be soluble to some degree in water at ordinary atmospheric temperatures. Very insoluble gases apparently are poorly scavenged. Soluble gases enter liquid water drops in one of three ways, and the same mechanisms operate both in and below the cloud. One way gases enter precipitation is simply by dissolving in the water. In this way, such gases as N_2O and CH_4 are removed; the amount removed is proportional to solubility. Very soluble gases are more efficiently scavenged than slightly soluble gases. In the second mechanism, the gas dissolves in the water and then undergoes reversible hydration or dissociation. This occurs with CO_2 and NH_3. The third mechanism involves dissolution of the gas in water followed by an irreversible reaction with other dissolved substances in the cloud water. This process occurs with SO_2 and NO_2.

In all cases, removal of the gas from the atmosphere depends on the subsequent participation of the cloud droplet in the precipitation process. If the cloud droplet evaporates before reaching the ground, the gases will reenter the atmosphere, or, in the case of irreversible reactions, a solid particle will be liberated.

Little is known about gas scavenging by snow. Engelmann (1968) reported a few experiments on bromine and iodine gas that showed very limited removal by snow.

Particle scavenging has received considerably more attention by researchers, but its processes, too, are only partially understood. Particle scavenging by rain includes at least three physically distinct processes, effective over different particle size ranges. Brownian capture occurs primarily in clouds, and is effective for particles less than about 0.1 μm diameter. This process relies on Brownian motion of air molecules to bring tiny particles into contact with cloud droplets, where they are collected; its effectiveness increases as particle size decreases.

Nucleation scavenging occurs during cloud formation as each individual cloud droplet forms (nucleates) on a separate particle (nucleus) which is thus captured by the growing droplet. This process is effective on at least partially soluble particles larger than about 0.1 μm. This includes the size range between 0.1 μm and 1 μm where dry deposition processes are least effective (see Fig. 75).

Impaction scavenging occurs after raindrops have grown large enough to fall. It can occur both in the cloud and below the cloud, but is most often associated with below-cloud scavenging.* It is effective on particles larger

---

**Below-cloud scavenging is frequently termed* washout, *and in-cloud scavenging* rainout. *However, these terms are unnecessarily imprecise and should be avoided in favor of the more physically descriptive* Brownian capture, nucleation, *and* impaction scavenging *wherever possible (Slinn, 1976a-in press).*

than about 5 μm diameter; these particles are vulnerable to capture by falling raindrops because they have too much inertia to follow the motion of air around a falling drop and thus impact on the drop.

Snow also scavenges particles by the same three mechanisms enumerated for rain. However, the relative importance of the three may be different in the case of snow. This may be due to a snowflake's slower fall speed, larger surface area, and complex air-flow field. Again, relatively little attention has been given to snow scavenging of particles.

Further discussion of the physics of scavenging processes may be found in Junge (1963), Engelmann (1968), Hales (1972), Hidy (1973) and Slinn (1976b--in press). These references also give methods for calculating scavenging by each of the individual physical processes described above. However, the two most frequently used methods for practical application are described below.

SCAVENGING CALCULATIONS

The removal of particles from air by precipitation processes has usually been treated as a single process that may be expressed quantitatively by the equations:

$$\chi = \chi_o \; exp \; (-\Psi t), \text{ and} \tag{3}$$

$$\chi = \chi_o \; exp \; (-\Lambda t), \tag{4}$$

where χ is the instantaneous concentration (g/m^3) of a contaminant in air after time t, χ_o is the concentration at the beginning of the scavenging process, Ψ is the in-cloud removal coefficient (per sec), and Λ is the below-cloud removal coefficient (per sec).

Little is known about the value of Ψ. This method is usually applied in situations where below-cloud scavenging is dominant, such as calculating depletion of contaminant concentration in the plume of an industrial stack due to rainfall within a relatively short distance from the stack. This method has been thoroughly discussed by Engelmann (1968), who gave recommended values of Λ under various conditions of rain, snow, and particle size. It will not be developed further here.

The second practical method (scavenging ratio method) involves the use of the empirical parameter W, the scavenging ratio, or washout ratio (Chamberlain, 1960), defined on a mass basis as

$$W = \frac{k\rho}{\chi} \quad , \tag{5}$$

where k is the concentration of any material in precipitation (μg/g), χ is its concentration in air (μg/m^3), and ρ is the density of air, taken as 1200 g/m^3. If χ can be estimated or measured, and W can somehow be specified, then k can be calculated from Equation 5. Deposition follows by multiplying k by the amount of precipitation.

The scavenging ratio method relies on estimates of W made by prior measurement of k and χ. Because k is measured at the ground, it includes materials scavenged both in and below cloud, by perhaps many separate physical mechanisms.

Although equations can be written (Slinn, 1976b--in press) to describe scavenging by each mechanism separately, it is not usually possible to supply the needed data to apply the equations. Then an empirical method (Eq. 5) is the best option we have.

The scavenging ratio method (Eq. 5) is not suitable for estimating close-in scavenging in individual stack plumes; the method described above (Eqs. 3 & 4) (Engelmann, 1968) should be used in that situation. Furthermore, the scavenging ratio method applies primarily to particle scavenging, although Engelmann (1971) gave *W* values for SO_2. Gas scavenging is better handled using the method described above (Eqs. 3 & 4), or that described by Hales (1972) and Hales *et al.* (1976--in press). The scavenging ratio method (Eq. 5) is best applied to calculations of average depositions over periods of a month or more in locations away from major point sources.

In most situations, χ is measured near the ground and is unknown in air entering the cloud. It would be desirable to know χ at cloud base, but it is not necessary. The empirical relationship of Equation 5 can be used as long as the χ used to estimate k is measured or estimated on the same basis as that used originally to calculate *W*. Additional aspects of this method can be found in Engelmann (1971) and Gatz (1976).

Over a period of a month or more, *W* varies primarily with the particle size of the contaminant. Available measurements are summarized in Figure 76. The measurements of Cawse (1974) at Chilton (United Kingdom) are shown for a number of different elements having different mass median diameters (Fig. 76a). These *W*-values were calculated from measurements made monthly in a year-round sampling program in a predominantly rural area. Dry deposition into the samplers is included. Cawse's data are compared (Fig. 76b) to those of Gatz (1976); the latter were measured in primarily convective summer rainfall near St. Louis, and exclude dry deposition. Both sets of measurements show a dependence of *W* on particle size. In addition, there is a suggestion that *W*-values increase with distance from cities, although part of the excess of Cawse's values over Gatz's results from the inclusion of dry deposition.

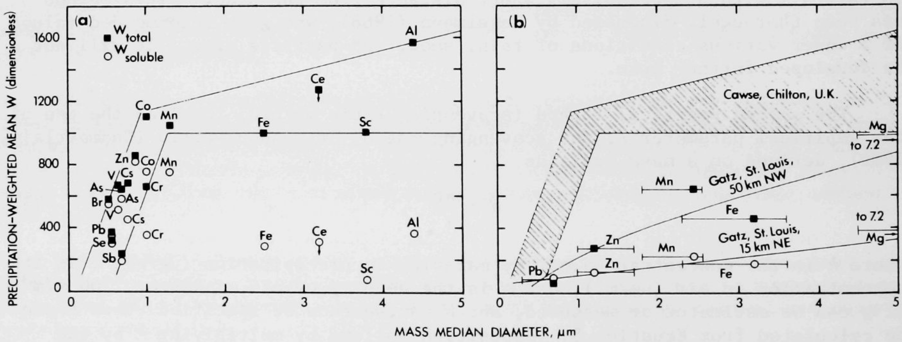


Fig. 76. Variation of Scavenging Ratio with Particle Size. (a) Data from Cawse (1974); (b) comparison of data from Cawse (1974) with data from Gatz (1974). Redrawn from Gatz (1976) (with permission, see credits).

Using Figure 76 and Equation 5, monthly or seasonal deposition of particulate matter may be estimated to a factor of about two, from a knowledge of contaminant concentration, size spectrum, and rainfall. The estimation may be made for a single location or as an average over a large area, as in the case of calculating precipitation input to Lake Michigan in the following section. An alternative method involving precipitation frequencies has been used in Europe to estimate sulfur deposited by precipitation (Rodhe and Grandell, 1972).

ATMOSPHERIC INPUT OF MATERIALS TO LAKE MICHIGAN

An immediate impression of the possible role of atmospheric inputs of chemical substances to the Great Lakes comes from a consideration of the sources of water to the individual lakes. Elder (1976) reported the fraction of each lake's annual input of water from precipitation on the lake surface (Table 28). Lakes Superior and Michigan, at the head of the Great Lakes chain, receive over half their water this way. The precipitation contribution decreases along the lake chain in the direction of water flow, as contributions to the inflow from upstream lakes increase. Although actual chemical inputs depend both on inflow rate and on the concentration of materials in each inflow mode, one can see that precipitation must be examined for its possible influence. However, since precipitation is falling at a given location only a few percent of the time, another possible atmospheric input mechanism, dry deposition, must also be evaluated.

Table 28. Fraction of Total Lake Water Input Due to Direct Precipitation on Lake (Data from Elder, 1976)

Lake	*Percent*
Superior	54
Michigan	53
Huron	24
Erie	11
Ontario	8

This section will begin by outlining the various methods that have been used to estimate atmospheric inputs (dry and in precipitation) to Lake Michigan. Some of the more frequently used parameters in these calculations will also be compared. Then all available results will be presented. Finally, the estimated atmospheric inputs will be compared to total inputs to provide a means of judging the relative importance of the atmosphere as a source for various elements.

A note of caution is necessary. Effects of chemical species added to a lake are not necessarily directly proportional to the inputs. Effects depend on the specific chemical form of the elements available in a lake. For example, Walton and Lee (1972) suggested that total reactive phosphate is the best measure of the amount of P available to lake organisms. In the case of P, it is possible to determine chemically the total reactive phosphate concentrations in precipitation and dry fallout. For other elements, the crucial chemical form may not yet be recognized, and even when it is, there may not yet be suitable methodology available to analyze for it. Finally, even if the crucial form is known and can be measured in precipitation and dry fallout, it is still the amount that becomes available in a lake that is really important. Much research will be necessary to quantify the relations between the amount of a given element that enters a lake from the atmosphere and the amount of its effective form in a lake.

These questions are very important and probably must be resolved before effects of chemical inputs to Lake Michigan are fully understood, but they are beyond the scope of the present report. We are limited here to a discussion of what is presently known about chemical inputs to Lake Michigan from the atmosphere. A previous section (Removal from the Atmosphere) discussed some of the methods that have been used to make these estimates.

METHODS

Two different general methods have been used to estimate atmospheric inputs to Lake Michigan. The first method involves direct measurement of inputs, and the second relies on calculations, based upon measurements of other basic parameters.

Measurements

Measurement of atmospheric inputs to a lake requires the collection and analysis of deposition samples at appropriate locations over or around the lake. Collection methods vary according to the purposes of the investigator. One type of collector is open to the atmosphere at all times to collect precipitation as well as dry-deposited material. A second type opens only during precipitation to collect only precipitation and exclude dry deposits. A third type has separate collectors for dry and wet materials and a movable cover that automatically covers the dry collector during precipitation and the precipitation collector during dry weather. In all collections of dry materials, it must be recognized that the collector is an artificial surface that is probably a poor representation of a lake surface. Thus, extrapolations from dry collections to dry input to a lake are uncertain.

Results of deposition measurements are generally expressed as rates, mass deposited per unit area per unit time. To estimate deposition on a lake surface, one must assume that deposition rates over water are the same as those measured over land.

Deposition is the product of the concentration of a material in precipitation and the amount of precipitation. Either or both can be different over water than over land. For example, Figure 77 compares concentrations measured at Lake Superior shore stations with those measured in samples collected from ships during June, 1973. For nitrate nitrogen, ammonia nitrogen, and chloride, mean concentrations at all shore stations exceed those over the lake. The problems of estimating precipitation over large lakes are also well known (Changnon, 1968b).

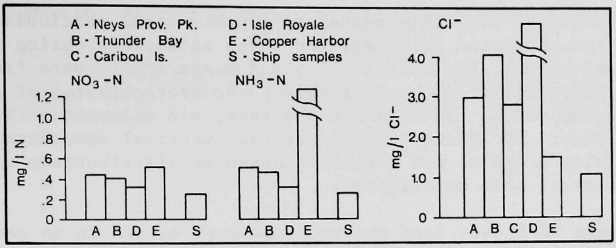


Fig. 77. Comparison of Contaminant Concentrations in Rain Samples Collected from Ships on Lake Superior with Those Collected at Onshore Sites, June 1973 (originally from Matheson, 1974--unpublished). From Elder (1976) (with permission, see credits).

Simple Calculation Models

Deposition Velocity

Deposition, D, of some material on a surface and the concentration of the material in air, χ, above the surface are related by the deposition velocity, V_d, discussed earlier. Once V_d has been determined for a given material, by empirical measurement of D and χ, it may be used with new χ-values to calculate D for some new point of interest. Generally, large variability is observed on an event or daily basis; the method is best used for weekly or monthly averages. The parameter V_d may refer only to individual deposition mechanisms, such as wet or dry deposition, or to their sum. Writers must take care to specify, and the reader to understand, which is meant in an individual situation.

Reported concentrations for various pollutants were given in the section on Air Quality; deposition velocities were discussed further, and observed values given, in the section on Removal from the Atmosphere.

Upwind-Downwind Concentration Differences

In general terms, this method requires measurement of concentrations of (*i*) some material in air upwind and downwind of a deposition surface, in this case Lake Michigan, and (*ii*) meteorological parameters that give the travel time over the Lake and the depth of the mixed layer. The average mass flux into the water, $\overline{F}$, is given (Whelpdale, 1974) as

$$\overline{F} = (HC_o\overline{u}/x_1)\ (1-C\ t_1/C_o)\ . \tag{6}$$

C_o and C are upwind and downwind concentrations in air, respectively; H is the mixing depth; $\overline{u}$ is the mean wind speed during the sampling period; x is the travel distance across the Lake; and t is travel time across the Lake, taken as $\overline{u}/x_1$.

This method assumes that (*i*) airborne concentrations are constant with height up to H, (*ii*) winds measured over land may be used to compute travel time and trajectories over water, and (*iii*) the system is near steady state, so that simultaneous samples upwind and downwind represent the same air.

Whelpdale (1974) used this method to compute total particulate deposition into Lakes Huron, Erie and St. Clair for a few situations during the warm season. Unfortunately, the only available H measurements were from Flint, Michigan, so his calculations were likely to be overestimates of the actual over-water mixing depth. If this was the case, his calculated fluxes would also be too large. Whelpdale pointed out that vertical concentration profiles, over-water mixing heights, and particle mass-size distributions are needed for maximum accuracy of this calculation.

Mean values of H over land and water were presented in an earlier section but must be measured for individual cases of interest, especially over water.

Emission Inventory × Transfer Efficiency

This method has been applied to estimating urban pollutant inputs to Lake Michigan. However, it could in principle be used also for natural pollutants, such as wind-raised soil dust, and for more extensive areas surrounding lakes if emissions and transfer efficiency estimates were available. The transfer efficiency is simply the percent of emissions in a given region transferred to the lake water.

Urban elemental emissions have been estimated by Winchester and Nifong (1971) for Chicago, Milwaukee, and northwest Indiana, and by Gatz (1975) for Chicago and northwest Indiana, using a different method (Table 29). See the original papers for details of the calculations. Gatz (1975) discussed the differences in the two estimates. We will not discuss them further here, but it is clear that large differences in estimates result from the different methods used, and that users of estimates from either method must be aware of their uncertainty.

A range of transfer efficiencies has also been proposed. Winchester and Nifong (1971) estimated a value of at least 10%, not including deposition in precipitation. Robbins *et al.* (1972) calculated transfer efficiencies varying with particle residence time in lake air and location along the southeastern shore of Lake Michigan, based on the fraction of time the surface winds blow toward the Lake. Values ranged from 5% for particles with 50-hr residence times, emitted from Gary, to 62% for particles with 0.1-hr residence times, emitted from Milwaukee. Overall, they estimated a mean transfer efficiency of at least 20%, not including precipitation deposition. More recently, Skibin (1973) estimated a transfer efficiency of at least 25% for Milwaukee, Chicago, and northwest Indiana aerosols. His estimate was based on the method of calculating deposition given by Van der Hoven (1968) for an assumed deposition velocity of 1 cm/sec (0.4 in./sec), a mean wind speed of 5 m/sec (∿16 ft/sec), and an emission height of 100 m (∿330 ft).

A final determination of transfer efficiencies must await accurate emissions and lake deposition measurements, not now available. However, the results of the model calculation by Gatz (1975), discussed below, gave values ranging from 3 to 15%, increasing with particle size.

A Simple Physical Model

Gatz (1975) has recently attempted an estimate of Chicago and northwest Indiana pollution input to the Lake. This calculation includes the new estimate of urban elemental emissions mentioned earlier. In addition, it includes

Table 29. Comparison of Emission Estimates Using Different Methods, metric tons/yr

	Winchester and Nifong, 1971	*Gatz, 1975*
Element	*Chicago, Milwaukee and NW Indiana*	*Chicago and NW Indiana*
Ag	3	
Al	45,000	7,800
As	44	69
B	4	
Ba	210	
Be	5	
Br	725	
Ca	37,000	
Cd	12	65
Cl	635	
Co	50	
Cr	100	130
Cu	3,200	750
Fe	86,000	22,000
K	15	
Mg	5,500	
Mn	4,600	800
Mo	46	
Na	1,400	
Ni	1,000	200
P	150	
Pb	2,200	6,100
S*	680,000	
Se	20	
Si	59,000	
Sn	13	
Sr	5	
Ti	2,400	930
V	610	370
Zn	3,900	1,560

**Particulate form only.*

calculations of both wet and dry deposition and takes account of differences in their rates between warm and cold seasons.

The dry deposition calculation relies on the deposition velocity, V_d, and a concentration varying with distance from the source. Values of V_d for dry processes varied with estimated elemental mass median diameters, using values measured by Cawse (1974). The observed relationship is shown in Figure 74. Deposition in precipitation was estimated using scavenging ratios, as discussed in a previous section. For further details of the calculation, see Gatz (1975).

RESULTS

All available estimates of atmospheric inputs of materials to Lake Michigan are summarized in Table 30. Note that the estimates of Winchester and Nifong

Table 30. Atmospheric Aerosol Inputs to Lake Michigan (to whole Lake from all sources, except as indicated), metric tons/yr

Element	*Winchester and Nifong, 1971* (1)*[†]	*Gatz, 1975** (2)*	*Klein, 1975 (3)*	*Edgington and Robbins, 1976*	*Elder, 1976 (4)*	*Murphy, 1976 (4)*
Ag	0.3		19			
Al	4,500	1,190	38,000			
As	4.4	2.6	81			
B	0.4					
Ba	21					
Be	0.5					
Br	72.5		2,500			
Ca	3,700		120,000			
Cd	1.2	3.2				
Cl	63.5		28,000			
Co	5		17			
Cr	10	7.3	210			
Cu	320	43	2,300			
Fe	8,600	2,320	47,000			
Hg			36			
K	1.5		62,000			
La			36			
Mg	500		51,000			
Mn	460	79	1,900			
Mo	4.6					
N					27,800-62,550[a]	
Na	140		15,000			
Ni	100	11				
P	15				1,390-2,780[a]	1,000
DRP						500
TRP						600
Pb	220	200		720 (1) 870 (3)		
S	68,000		510,000			
Sb			79			
Sc			25			
Se	2.0		39			
Si	5,900		40,000			
Sn	1.3					
Sr	0.5					
Th			66			
Ti	240	120				
V	61	15	120			
Zn	390	110	3,300			

**Lower limits from Chicago, Milwaukee, and northwest Indiana. Corresponding lower limits for the 20% transfer efficiency proposed by Robbins et al. (1972) or the 25% efficiency proposed by Skibin (1973) may be obtained by multiplying these figures by 2.0 and 2.5, respectively.*

***For southern basin, from Chicago and northwest Indiana only.*

[†] *Number in parentheses refers to method of estimation: (1) emissions × transfer efficiency, (2) simple physical model, (3) concentration × V_d, (4) measurement.*

[a] *Based on N deposition rates of 40-90 mg/m^2/mo and P deposition rates of 2-4 mg/m^2/mo (see text).*

(1971) and Gatz (1975) represent only pollutant inputs from certain industrial areas.

Nutrients

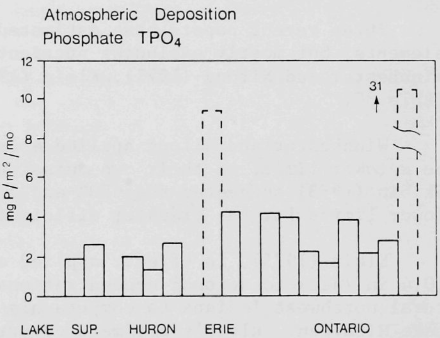
Phosphorus inputs to Lake Michigan have been measured only by Murphy (1976). However, Elder (1976) reported results of P inputs to the other Great Lakes that could be used for comparison with Murphy's results. Murphy sampled rain at six locations around Lake Michigan and estimated an annual input, via precipitation only, of 1000 tons* of total P. In addition, he estimated that 600 tons of this were total reactive phosphorus (TRP), of which 500 tons were dissolved.

Elder (1976) reported preliminary results of the International Joint Commission program to estimate atmospheric inputs to four of the five Great Lakes. Unfortunately, Lake Michigan was not included, since it is completely within the United States. Nevertheless, the P results may be used for comparison, and the N results are the only ones available for this important nutrient.

Phosphorus deposition rates, dry plus precipitation, for Lakes Superior, Huron, Erie, and Ontario are shown in Figure 78. The dashed results were collected on islands and are suspected to include samples contaminated, either directly or indirectly, by bird droppings. These samples were omitted in

Fig. 78.

Measured Deposition Rates of Phosphorus in Collectors around Lakes Superior, Huron, Erie, and Ontario (originally from Matheson, 1974--unpublished). From Elder (1976) (with permission, see credits).

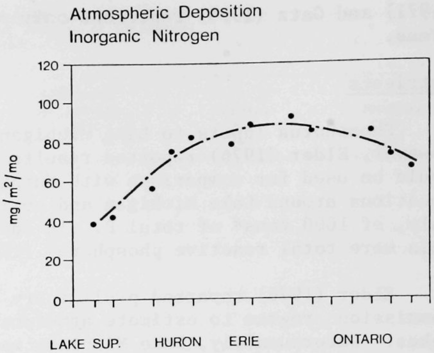


computing the range of P inputs shown. The range of 1390-2780 tons/yr, shown in Table 30, was computed using the surface area of Lake Michigan together with 2-4 mg/m^2/mo as typical deposition rates. The lower end of the range is typical of Lakes Huron and Superior, and perhaps it represents Lake Michigan also. However, the presence nearby of large concentrations of population and industry, and extensive farming operations, would suggest that Lake Michigan would be subject to higher deposition rates than the more remote Lakes Superior and Huron. In any event, the range 1390-2780 tons/yr for total deposition is consistant with Murphy's value of 1000 tons/yr from precipitation only. However, it should be kept in mind that smaller deposition rates for three constituents were observed in ship samples than from those collected at land sites (Fig. 77). Presumably, the same would also be true for P.

**Tons = metric tons (see footnote, p. 82).*

Fig. 79.

Measured Deposition Rates of Inorganic Nitrogen in Collectors around Lakes Superior, Huron, Erie, and Ontario (originally from Matheson, 1974--unpublished). From Elder (1976) (with permission, see credits).



Preliminary deposition rates for inorganic N, defined as nitrate-nitrogen plus ammonia-nitrogen, are shown in Figure 79. The deposition-rate range of 40-90 mg/m^2/mo was used to calculate the range of possible values for Lake Michigan shown in Table 30. Again, the likelihood of smaller deposition rates over the lakes must be considered.

Other Elements

Three recent papers have estimated inputs of a wide variety of trace elements, but mostly excluding nutrients, to Lake Michigan. The results of Winchester and Nifong (1971), Klein (1975), and Gatz (1975) are also given in Table 30.

Winchester and Nifong applied a transfer coefficient of 10%, considered to be a lower limit, to their own emission inventory. Robbins *et al.* (1972) and Skibin (1973) suggested that 20% and 25%, respectively, should be considered lower limits for the transfer efficiency.

Klein (1975), in effect, applied a deposition velocity of 1 cm/sec (0.4 in./sec) to aerosol concentrations measured by Dams *et al.* (1970) in semi-rural northwest Indiana to compute his estimate of atmospheric contribution to Lake Michigan. Klein's estimate covers the entire Lake and represents natural as well as pollutant aerosols. His 1 cm/sec deposition velocity was chosen to include both dry and precipitation deposition processes.

The estimates of Winchester and Nifong (1971) and Gatz (1975) are limited to Lake inputs of pollutant aerosols from the southeastern lakeshore. Gatz considered only deposition into the southern basin of the Lake, but little additional deposition of pollutant aerosols from Chicago or northwestern Indiana should be expected.

Edgington and Robbins (1976) have provided two separate estimates of atmospheric inputs of Pb to Lake Michigan. The first, 720 tons/yr, results from a transfer efficiency of 25% applied to estimated Pb emissions from Chicago-Gary of 2900 tons. The second, 870 tons/yr, results from multiplying a deposition velocity of 1.6 cm/sec (0.6 in./sec) by an assumed average concentration over the Lake of 30 ng/m^3. This presumably represents all atmospheric

Pb sources to the Lake. Assuming thorough mixing in the lake water and uniform deposition in the bottom sediments, these whole-lake estimates reduce to annual depositions of 220 and 270 tons, respectively. These values are very close to Edgington and Robbins' estimated total Pb input to southern basin sediments of 270 tons/yr based on a Pb-210 tracer method.

DISCUSSION

The importance of the atmosphere as a source of nutrients and other elements to Lake Michigan cannot be judged solely from measured or calculated annual inputs. The atmosphere's role is clear only by comparing atmospheric inputs to total lake inputs from all sources.

Klein (1975) has calculated the total input of 28 elements to Lake Michigan. He assumed steady state conditions, so that input was taken as equal to the combined outputs from water outflow to Lake Huron and sediment deposition on the bottom of the Lake. Outflow to Lake Huron was computed as the product of the mean annual discharge and the mean elemental concentration in Lake Michigan waters. These concentrations were taken from literature values (averages) at 20 locations in the Lake. Klein cautioned that such averages might not accurately represent the mean for the whole Lake since only 20 sites were sampled. Furthermore, 12 of these were within 16 km (10 mi) of shore, and 14 were in the southern basin. Loss to the bottom sediment was based on published total sedimentation rates and elemental concentrations in the sediments at the same 20 sites.

Klein's estimates of total annual inputs are shown in Table 31. Shown in the same table are tributary inputs for the soluble portion of many of the same elements; most of these were measured by Robbins *et al.* (1972), with the remainder being unpolluted stream inputs calculated by Winchester and Nifong (1971), using data of Turekian (1969). Thus, it is possible to test Klein's supposition that total atmospheric inputs exceeded tributary inputs of the soluble elements examined. In general, some additional tributary input should be insoluble, and there may be other sources, such as direct outfall of industrial water pollutants into the Lake.

Klein's estimates of total inputs exceed the tributary inputs of soluble materials substantially for all but three elements--Ca, Na, and Sr. In general, however, it appears that with allowances for the possible uncertainties mentioned above, the total input values can be used as a basis for evaluating the importance of atmospheric inputs.

The two nutrient elements, P and N, are a special problem because they are not included among Klein's 28 elements. However, other estimates are available for total inputs of these nutrients. Adamkus (1975--personal communication) has provided a value of 5500 tons/yr as the total input of P to Lake Michigan for 1974. Murphy's (1976) total precipitation input represents 18% of this value. The range of total atmospheric inputs estimated from Elder's (1976) preliminary data represent 25-50% of the total amount of P received by the Lake. For N, total lake inputs are available from Upchurch (1976) for Lakes Superior and Huron. Elder (1976) gave preliminary values for the percent of total N inputs to those lakes from the atmosphere; the two values for N appearing in Table 31 are for Lakes Superior and Huron, respectively.

Table 31. Relative Contribution of Atmospheric Input to Total Lake Input

	Lake Inputs, metric tons/yr		*Percent of Total Lake Input via Atmosphere*					
Element	*Whole Lake Soluble Tributary Inputs**	*Total Lake Inputs***	*Murphy, 1976*	*Elder, 1976*	*Edgington and Robbins, 1976*	*Klein, 1975*	*Gatz, 1975*	*Winchester and Nifong, 1971*
Ag	10[a]	21				90		1.4
Al	13,000[a]	420,000				9	0.3	1.1
As	65[a]	160				51	1.6	2.8
B	330[a]							
Ba	730	6,000						0.4
Br	650[a]	3,000				83		2.4
Ca	2,100,000	2,100,000				6		0.2
Cl	25,000[a]	780,000				4		0.0
Co	6.5	100				17		5
Cr	170	720				29	1.0	1.4
Cu	140	510				451	8.4	63
Fe	1,460	210,000				22	1.1	4.1
Hg		7.3				493		
K	84,000	270,000				23		0.0
La		280				13		
Mg	660,000	730,000				7		0.1
Mn	470	6,200				31	1.3	7.4
Mo	290							
N				48–66[d]				
Na	510,000	300,000				5		0.0
Ni	510							
P	650[a]	5,500[b]	18	25–50				0.3
Pb	100[a]	870[c]			83–100		23	26
S	180,000[a]	510,000				100		13
Sb		19				416		
Sc		52				48		
Se	6.5[a]	9.1				428		22
Si	44,000[a]	2,300,000				0.1		0.2
Sr	6,900	5,900						0.0
Th		53				12		
Ti	100[a]							
V	29[a]	390				31	3.8	16
Zn	180	2,900				114	3.8	13

Robbins et al. (1972), except as noted.

***Klein (1975), assuming total input is equal to output to Lake Huron plus that to bottom sediments, except as noted.*

[a] *Winchester and Nifong (1971) using data of Turekian (1969).*

[b] *Adamkus (1975--personal communication) quoted by Murphy (1976).*

[c] *From sedimentation only, estimated from data of Edgington and Robbins (1976) (see text).*

[d] *Estimated values for Lakes Superior and Huron, respectively (see text).*

In regard to Pb, Klein (1975) has not provided a value of total input. However, we can make a partial estimate using the data and assumptions of Edgington and Robbins (1976). The portion of input equal to the output via sedimentation can be estimated by extrapolating their values (30 tons/yr of natural Pb deposition, and 240 tons/yr of man-made Pb deposited in the southern basin) to the whole Lake. One can reason that natural Pb deposition to the sediments should be uniform over the whole Lake. Similarly, the man-made Pb should deposit uniformly since almost all of it comes from the atmosphere, and we assume thorough mixing in the lake water before sedimentation. With this reasoning, a partial annual input of 870 tons was calculated.

The difference in inputs of Pb attributable to the atmosphere as given by Edgington and Robbins (1976), Gatz (1975), and Winchester and Nifong (1971) is substantial, but depends largely on the validity of the assumptions just made in estimating total lake input. Perhaps mixing in the lake water is really not so fast that uniform sediment deposition can be assumed, and perhaps most loss to the sediments occurs in the southern basin. If so, the three estimates come into closer agreement. Then, clearly, most Pb in the Lake would be man-made, entering via the atmosphere.

There are also considerable differences between input estimates for many other elements, although it must be kept in mind that one author (Klein, 1975) attempted to give total input to the Lake via the atmosphere, while others calculate only input from populated industrial regions.

In comparing data of Gatz (1975) and Winchester and Nifong (1971), much of the variation results from different emissions estimates. Furthermore, Gatz's model predicts differing transfer coefficients for different elements while Winchester and Nifong applied a constant coefficient to all elements. A relatively small difference also stems from the fact that Gatz computed only southern basin input.

The variation in results between Gatz (1975) and Klein (1975) occurs largely because of different assumptions concerning ambient concentrations in air. Gatz used a composite model aerosol selected from a survey of many published values, while Klein used the mean of a single day's observed values in semi-rural northwestern Indiana. He also used a constant value over the Lake while Gatz allowed concentrations to decrease with distance from their source.

Klein's results appear quite uniformly high by comparison with his total input values (Table 30). For six elements (Cu, Hg, S, Sb, Se, and Zn), atmospheric inputs are 100% or more of total lake input, and four of these are over 400%. Also, an additional three elements have values between 50% and 99%. Only six of the 24 elements Klein considered had atmospheric contributions less than 10% of total input. These results probably stem from using concentrations over land on a single day to represent year-round concentrations over the Lake.

To summarize, Table 30 shows that atmospheric input of nutrients to Lake Michigan accounts for 18% or more of P inputs and 50% or more of N inputs. Among other elements, Gatz listed only Pb as having atmospheric inputs greater than 10% of the total; Winchester and Nifong's values agreed on Pb, and they added Cu, S, Se, V, and Zn to the list. In addition to those, Klein's results added Ag, As, Br, Co, Cr, Fe, Hg, K, La, Mn, Sb, Sc, and Th to the over-10%

category. Edgington and Robbins suggested that almost all Pb in the Lake arrives via the atmosphere.

SUMMARY AND CONCLUSIONS

A number of estimates are now available for atmospheric inputs of nutrients and a large number of other elements to Lake Michigan. An estimate of total input to the Lake is also available so that the relative importance of atmospheric inputs can be judged. Unfortunately, estimates of both total and atmospheric inputs are currently subject to considerable uncertainty.

Estimates of atmospheric inputs are based on deposition measurements as well as several different kinds of calculations. All available estimates indicate that atmospheric inputs of P, N, and Pb account for at least 20% of all inputs for these elements. There is considerable disagreement on the remaining elements treated; however, two or more authors agreed that at least 10% of the total inputs of Cu, S, Se, V, and Zn reach the Lake via the atmosphere.

We probably will not have an accurate picture of actual elemental inputs to Lake Michigan until we measure them properly. This should include separate measurements of deposition in dry form and in precipitation, in both warm (stable) and cold (unstable) seasons. Moreover, until good deposition and air quality measurements and good simultaneous meteorological observations are available for a number of elements, we won't know which models are correct.

Current experience suggests that measurements needed to make progress on estimating atmospheric contributions to the Great Lakes include: (*i*) elemental concentrations (including vertical profiles) and size distributions over the lakes, as a function of atmospheric stability; (*ii*) mixing heights over the lakes, as a function of stability; and (*iii*) elemental emissions inventories, for both urban and non-urban sources.

RESEARCH NEEDS

Atmospheric research needs of the Lake Michigan region center on observations and measurements over the Lake itself. Considering the difficulty of making such measurements, it is understandable that, to date, these have been neglected in comparison with ones that are easier to make.

Three general areas appear to be most in need of additional work:

(*i*) Atmospheric aspects of the Lake's water budget.

(*ii*) Behavior of the Lake boundary layer.

(*iii*) Pollutant distributions over the Lake.

An understanding of the Lake's water budget is an important aspect of assessing regional water supply. Two atmospheric parameters, precipitation and evaporation over the Lake, are important terms in the water balance equation. Measurement or accurate estimation is very difficult and uncertain, but must be done before the Lake water budget is adequately understood.

Improved measurements over the Lake of such standard meteorological parameters as cloudiness and wind are also needed. Both are important to evaporation from the Lake. Cloudiness should be amenable to study using satellite photographs now available.

The other two areas where more information is greatly needed both relate to the lowest layers of the atmosphere over the Lake. The first is concerned with describing and understanding that particular layer of the atmosphere (the boundary layer) in terms of its basic meteorological processes. The second is concerned with pollutant distributions in, and deposition of materials from, this layer.

We know generally that the lower atmosphere over the Lake experiences extremes of stable and unstable conditions in summer and winter, respectively, and that these conditions are very important to pollutant dispersal and deposition. What is lacking are quantitative details of these processes:

(*i*) Frequencies of occurrence of various depths of the stable/unstable layer.

(*ii*) Average daily, seasonal, and annual variations of the boundary layer depth.

(*iii*) Variation of average boundary layer conditions with distance from shore along the wind (in the direction the wind is blowing), for various wind directions.

The gathering of this information would aid considerably our ability to calculate pollutant dispersal over the Lake; measurements of the physical characteristics and distribution of pollutants are also needed. Particularly vital are:

(*i*) Vertical and horizontal distributions of pollutants over the Lake for at least three regimes: stable (summer), unstable (winter), and transitional (spring and fall).

(*ii*) Particle size distributions, as a function of distance from shore along the wind.

(*iii*) Measurements of wet and dry deposition onto the Lake.

The needed research ranges from analysis of already-available data to measurements for which techniques do not now exist. In between are studies for which techniques exist, but their application over the Lake surface is either inconvenient or very costly. In many areas where research is needed, trained scientists and adequate organizational structures for doing the work already exist; only the necessary financial resources must be found.

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CREDITS

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